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PROGRESS REPORT

DEVELOPMENT OF LOW TEMPERATURE DIELECTRIC COATINGS FOR ELECTRICAL CONDUCTORS

ANNUAL SUMMARY AND 12TH QUARTERLY REPORT

BY

K.N. MATHES

JULY 15, 1964

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Annual Summary and 12th Quarterly Report

July 15, 1964

DEVELOPMENT OF LOW TEMPERATURE DIELECTRIC COATINGS FOR ELECTRICAL CONDUCTORS

INTRODUCTION

This report includes conclusions and a summary of the technical accomplishment under the subject contract during the last year as well as more detailed results of work during the last quarter. For details of the earlier work reference may be made to Quarterly Reports dated October 15, 1963, January 15, 1964 and April 15, 1964. In addition, attention is drawn to reports dated July 16, 1962 and July 15, 1963 for summaries of the first two years' effort on which the work of the last year is based.

The primary objective of the effort during the last year has been directed toward the development and evaluation of stranded round wire and of ribbon cable particularly suitable for application at cryogenic temperatures. The electrical properties of two film dielectrics, H-film and FEP Teflon, have been evaluated at high as well as cryogenic temperatures, since a better understanding of these materials permits interpretation of the results with both round and ribbon cables. The detailed results have in consequence been divided into three sections.

Electrical Characteristics of FEP and H-film

Stranded Round Cable

Ribbon Cable

In the coming year effort will be directed to the development and evaluation of connections and terminations for round and ribbon cable which will withstand exposure at cryogenic temperatures and also later maintain adequate electrical properties when exposed to adverse conditions such as frost, moisture and contaminants. The problem of removing insulation to make the connections will also be investigated.

SUMMARY AND CONCLUSIONS

Round Stranded Cable

In the final stages of the subject program, emphasis has been placed on stranded cable wrapped with a lapped layer of .001 inch H-film (du Pont's aromatic polyimide film) over a concentric bundle of stranded wire. The individual strands of the bundle were coated before stranding with ML enamel (du Pont's aromatic polyimide). Since the individual strands are insulated, each wire can be considered as a separate conductor. When grouped together, the bundle also can be considered as one conductor for which the ML enamel provides extra insulation in addition to the H-film.

ML Enamel

The very thin, film coating of ML enamel will always have some discontinuities or points of inadequate insulation along its length. The faults are widely spaced and seldom "register" between wires in the bundle. Consequently, low voltage failure between individual wires is unlikely. If faults do register, they can be detected and easily cut out. However, if a stranded cable is exposed to liquid water, voltage failure is much more likely and in such cases ML enamel as the only dielectric cannot be recommended without some reservation. It should be remembered that frost and liquid water may form on a cold cable as it returns to room temperature, but that ice at low temperatures is a good dielectric.

Moreover, a considerable difference in the quality of ML enamel has been indicated in the course of this work. (i.e., The continuity in the #16 stranded cable was much superior to the #26 cable). It is probable that ML enamel alone may provide adequate insulation if special care is taken to reduce the number of faults. Continuous dielectric test during manufacturing can be recommended as one approach to the solution of the problem, although at increased wire cost. The importance of adequate cure to obtain low temperature flexibility in ML enamel should be emphasized here, too.

ML enamel possesses relatively very good dielectric characteristics at room temperature and at liquid helium temperature its dielectric loss is as low or lower than Teflon at room temperature.

ML enamel does provide very much less insulation build than conventional cable insulation and where it can be used it will permit very significant savings in space and weight, particularly with small wires. Without question, properly cured ML enamel is the most flexible wire insulation at cryogenic temperatures. It seems almost impossible to crack an ML stranded construction by flexing it even in liquid helium, although conventional insulation is shatter brittle at very low temperatures.

ML enamel has relatively very good mechanical properties, as can be demonstrated by its ability to withstand a difficult stranding operation without damage. Its outstanding resistance to cut through at both very low and very high temperatures has been demonstrated in previous work.

In final conclusion, ML enamel alone is considered to provide adequate, low voltage insulation on solid conductors for use over a wide range of temperatures if properly controlled in manufacture and selected in use.

H-film and HT-1 braid

A lapped layer of .001 inch H-film breaks down at a surprisingly high voltage if it is sufficiently overlapped. In the subject work the approximate 2/3 overlap on the #26 cable is very adequate, while the 1/2 lap on the #16 cable is marginal. With a very tight wrap, the H-film clings closely to the wire - so tightly on the #26 cable that it could be unwrapped only with considerable difficulty. The dielectric loss is reasonably low at room temperature and in liquid helium is as low as Teflon at room temperature.

The untreated HT-1 braid over the H-film was used to provide resistance to abrasion and protection against mechanical damage as the outer shield was braided on. The short run samples without the HT-1 braid indicated that nothing was gained by using the braid. Instead the HT-1 braid imposed penalties of added space and the absorption of moisture.

The flexibility of the H-film wrapping at cryogenic temperatures is difficult to analyze. The first samples of #16 cable evaluated exhibited remarkable flexibility in liquid helium. The cryogenic flexibility was apparently damaged by moisture exposure. Unfortunately, most recent samples of H-film taped #16 cable have cracked badly even on a 1 3/4" mandrel in liquid helium. The #26 H-film wrapped cable seems to be little better in cryogenic flexibility than extruded Teflon.

It is possible (perhaps likely) that, at its present stage of development, H-film is not a uniform and well controlled product. Like ML enamel, H-film may be sensitive to undercure and perhaps to moisture, particularly in the undercured state. Additional study would appear to be needed.

The only justification for using H-film, with the inherent disadvantages of taping, lies in the potential for improved flexibility at cryogenic temperatures. If this flexibility cannot be attained, then extruded Teflon is a better choice. Very recently, very thin wall extrusions of FEP* Teflon have become available and it should be possible to obtain such extrusions over ML coated wire. The early work indicated, however, that the higher extrusions temperature of TFE** Teflon caused problems in that gassing of the underlying ML enamel resulted in poor continuity of the extrusion.

Ribbon Cable

In this program, ribbon cable has been constructed from H-film bonded by hot pressing with layers of FEP-Teflon adhered to one or both surfaces of the H-film as needed. In effect, the flat conductors and the copper fabric shield (if used) become encased in FEP-Teflon and thereby adhered on both sides to H-film. The H-film serves to provide a completely non-thermoplastic insulation which will not flow during the hot bonding operation. However, the H-film can be punctured if too thin or if excessive pressure is used.

*Polyfluoroethylene-propylene made by du Pont.

**Polytetrafluoroehtylene made by du Pont.

All of the six samples of H-film ribbon cable evaluated in this program possess remarkable flexibility even in liquid helium if the test specimens are not twisted or bowed in bending. The sensitivity to twisting at low temperatures, however, does constitute a limitation in use. While delamination between the H-film and the FEP Teflon has never been observed at room or cryogenic temperature, adhesion is markedly reduced by aging at 250C (but not at 120C). Of course, adhesion to Teflon is always suspect and such delamination is not unexpected.

The electrical properties of all six ribbon cables are very good except for multiple spots of low breakdown voltage to the shield in samples #4 and #5. This breakdown difficulty was overcome by increasing the H-film thickness from .001 to .002 inches in sample #6. A single shield appears to provide adequate electrical isolation. However, the AC resistance along the copper fabric shield appears to be high enough to introduce considerable electrical loss which may be an adverse factor in long runs.

Round Stranded versus Ribbon Cable

The "battle" between the advocates of round and ribbon cable is likely to continue! Both types appear to have advantages and disadvantages. Understandably, because ribbon cable is new, more problems will be involved in its application until the difficulties can be worked out.

Inherently, ribbon cable for the same current carrying capacity will take less space and weigh less than round, bundled conductors, particularly if multiple ribbon cables can be stacked and clamped one on top of the other. Such multiple stacking will help the performance of ribbon cable at cryogenic temperatures, since the rigid laminated structure will tend to stay flat and should not twist. On the other hand, round cable may have advantages in long runs where it is laid rather loosely in ducts. Where current carrying capacity is not important, multiple strands of small ML film coated wire may take much less space and weigh less than an equivalent number of conductors in ribbon cable, which must be larger.

The electrical comparison of bundled round and ribbon cable depends upon the characteristics desired in each specific application. ML coated wires in a single stranding provide the maximum of conductors in a limited space, but the individual wires cannot be electrically shielded one from the other. The capacitance between conductors in ribbon cable is intrinsically low, but between conductors and shield it is high. The capacitance between unshielded conductors in a round cable is high but can be low to the shield if sufficient insulation is provided.

Subject to the discussion above, both stranded round and ribbon cables can be made which have quite acceptable characteristics at low temperatures. In fact, the electrical properties of both are better at very low than at normal temperatures.

Dielectric Properties of FEP and H-Films

While the basic purpose of the subject program involves the development of wire and cable insulation particularly suitable for operation at cryogenic temperatures, much has been learned about the rather basic characteristics of dielectrics at very low temperatures. During the last year the dielectric characteristics of both FEP and H-film have been extensively measured at not only low but at high temperatures as well (for H-film from -269 to 300°C). While the frequency range of 50 to 10,000 cps is useful, it is regrettable that higher frequencies could not be investigated because available measuring equipment lacks sensitivity or the ability to use guarded leads which are essential to such work in cryostats.

The dielectric measurements on films have provided the base for understanding the dielectric performance of both round and ribbon cable which incorporates these films in their construction. It is interesting that dielectric absorption can produce effects of rather significant properties at liquid nitrogen temperatures and that dielectric absorption is still measurable at 4.2°K. Such effects have seldom been observed and, in fact, some references in the literature have stated the theoretical but incorrect conclusion that dielectric absorption must disappear at cryogenic temperatures.

It is possible in the long run that the basic understanding of dielectrics to be gained in the subject program may prove to be at least as and perhaps more valuable than the cryogenic insulators developed.

OBSERVATIONS AND SUMMARY OF TEST RESULTS

In this report all of the results with stranded round cable are grouped together and later results with ribbon cable are handled in a similar fashion. Since the more fundamental dielectric measurements on FEP and H-film are important to both round and ribbon cable, these measurements will be discussed first.

Dielectric Measurements on FEP and H-Film

In order to understand better the measurements of capacitance and dissipation factor on both round and ribbon cable, it became essential to make such measurements on the materials from which these cables are constructed. It is difficult to make significant measurements on fibrous structures, such as HT-1 braid. Fortunately, these measurements were not necessary since round cables had been made both with and without the braid. Thus, the effect of the braid could be determined by differences. It is extremely difficult also to make accurate AC measurements of ML-enamel on wire* since no suitable electrode for round wire has been developed so far which can withstand immersion in liquid helium without damage. However, it is believed that the polymer characteristics of ML-enamel are much like those of H-film, so that measurements of H-film will be at least helpful in considering the properties of the enamel.

Electrodes on film are also a source of difficulty. Several problems can be listed:

1. Cohesions and adhesion to the film with temperature cycling.

2. High resistance in the electrodes themselves.

3. Errors due to electrostatic "fringing".

*In previous work the AC properties between wires lying side by side have been measured, but these measurements are not adequate for the purpose here.

These difficulties often work against each other. For example, thin evaporated gold electrodes exhibit good adhesion but have high electrical resistance, particularly on slightly rough surfaces. The error from a slight loss of electrode adhesion is decreased with thick samples, but the error due to fringing in this case increases. Guarded electrodes are difficult to make and in cryogenic work cause trouble because of occasional low impedance between the guard and measuring electrodes. Different electrode systems were checked by measuring capacitance at 23C before and after immersion in liquid helium. If no significant change in capacitance or visual damage occurred, adhesion and cohesion was felt to be adequate. A resistance of 0.5 ohms between points on opposite sides of the electrode was acceptable since relatively very little error was then introduced even for very low values of tan δ at 10,000 cps, the highest frequency used. (If higher frequencies are considered an even lower electrode resistance would be needed).

Many electrode systems have been investigated. So far no suitable electrode system has been developed for TFE Teflon film (all the specimens have a slightly rough surface). Suitable electrodes for FEP and H-film have been made with evaporated gold backed up by a coating of #4132.du Pont silver paint. Opposite electrodes,1 and 1¼ inch in diameter, have been used with .005 inch (nominal) film. Actual measurements of film thickness and electrode diameter were made at 23C before and after exposure at both low and high temperatures. Both FEP and H-film exhibited remarkable dimensional stability. However, it is extremely difficult to measure film thickness with accuracy.

The calculated values of dielectric constant for both FEP and H-film are given in Table I. It should be recognized that the absolute value is subject to the error in thickness measurement and as a result of fringing.* Moreover, the very considerable effort needed to measure the electrode size and the specimen thickness at low and high temperatures has not been judged worthwhile. Consequently, the results in Table I should be considered primarily in a comparative sense.

It should be noted in Table I that the H-film was held overnight at 60°C and 200°C as the temperature was increased to 300°C. In this way the effect of absorbed moisture could be investigated. As the temperature was decreased, it was held overnight at 100C for experimental convenience so that on the following morning the temperature could be decreased quickly to room temperature. The specimens were measured, hopefully, before they could pick up much moisture. (The use of a dissector would have improved these results).

It is useful in Table I to compare the values after holding at 60 and 200C. In both cases the dielectric constant decreased indicating loss of moisture (unless, as is unlikely, curing or molecular rearrangement is involved). If loss of moisture is still occurring at 200°C, it must be held tenaciously, although only a very small amount may be involved. The values at 100C and 25C after high temperature exposure show by comparison how much moisture absorption affected the initial results at these temperatures.

*Very accurate measurements of dielectric constant can be made by a two liquid immersion technique which is not suitable at low or very high temperatures.

TABLE 1

Dielectric Constant*

- Films -

Temp. °C	Spec. No.	.005" H-film 0.1Kc	.005" H-film 1Kc	.005" H-film 10Kc	.005" FEP-Teflon 0.1Kc	.005" FEP-Teflon 1Kc	.005" FEP-Teflon 10Kc
23°C	1	3.76	3.75	3.73	2.13	2.12	2.12
	2	3.74	3.73	3.71	2.14	2.13	2.13
	3	3.69	3.68	3.66	2.12	2.12	2.12
-196°C	1	3.32	3.31	3.30	2.15	2.15	2.15
	2	3.25	3.24	3.24	2.15	2.15	2.15
	3	3.28	3.27	3.26	2.17	2.17	2.17
-269°C	1	3.24	3.24	3.23	2.14	2.14	2.14
	2	3.18	3.18	3.18	2.15	2.15	2.15
	3	3.17	3.17	3.17	2.16	2.16	2.16
-60°C	1	3.42	3.41	3.40	2.09	2.09	2.09
	2	3.42	3.41	3.42	2.12	2.12	2.11
	3	3.38	3.38	3.38	2.11	2.11	2.10
60°C	1	3.30	3.29	3.28			
after 18 hours	2	3.26	3.25	3.24			
	3	3.22	3.21	3.20			
100°C	1	3.24	3.23	3.22	2.05	2.05	2.05
	2	3.22	3.20	3.19	2.08	2.08	2.08
	3	3.18	3.17	3.16	2.06	2.06	2.06
150°C	1	3.22	3.21	3.19	2.01	2.01	2.01
	2	3.19	3.18	3.17	2.03	2.03	2.03
	3	3.15	3.14	3.13	2.03	2.03	2.03
200°C	1	3.18	3.18	3.17	1.98	1.98	1.98
	2	3.15	3.15	3.14	2.01	2.01	2.01
	3	3.12	3.11	3.10	2.01	2.01	2.01
200°C	1	3.13	3.13	3.12			
after 17 hours	2	3.11	3.10	3.09			
	3	3.08	3.07	3.07			

*Approximate value uncorrected for edge effects or changes in specimen dimension with change in temperature.

TABLE 1 (Cont'd)

Dielectric Constant*

- Films -

Temp. °C	Spec. No.	.005" H-film 0.1Kc	1Kc	10Kc	.005" FEP-Teflon 0.1Kc	1Kc	10Kc
250°C	1	3.09	3.09	3.08			
	2	3.05	3.05	3.05			
	3	3.04	3.04	3.03			
300°C	1	3.01	3.00	2.99			
	2	2.97	2.97	2.96			
	3	2.96	2.95	2.95			
100°C	1	3.09	3.08	3.08	2.06	2.06	2.06
after above	2	3.06	3.05	3.05	2.09	2.09	2.09
(held overnight)	3	3.04	3.03	3.02	2.09	2.09	2.09
25°C	1	3.40	3.39	3.38	2.10	2.10	2.10
	2	3.28	3.27	3.25	2.13	2.13	2.13
	3	3.14	3.13	3.12	2.13	2.13	2.13

*Approximate value uncorrected for edge effects or changes in specimen dimension with change in temperature.

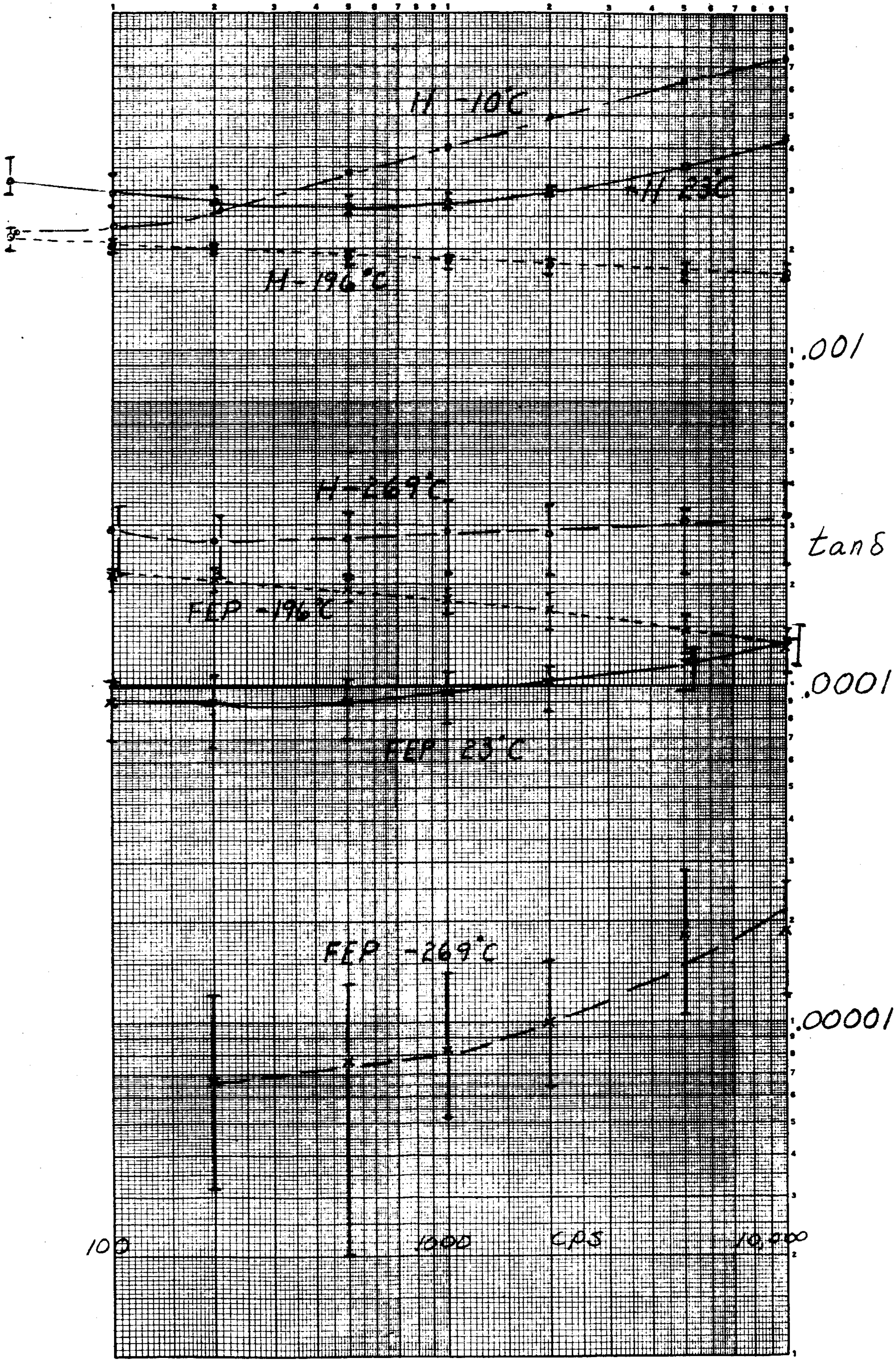


Figure 1: Dissipation Factor (tan δ) versus Frequency for FEP and H-films at 23, -196 and -269°C

It should be noted that no similar significant change occurred in the FEP since, as expected, it seems unaffected by absorbed moisture. The change of dielectric constant as a function of temperature is interesting. In an ideal non-polar material, the dielectric constant will decrease slightly as temperature decreases (primarily due to change in density) and for FEP Teflon this is true from 200°C to -196°C. Very little change occurs between -196°C and 269°C perhaps because in this temperature range the density also changes very little. The almost constant value of dielectric constant as a function of temperature confirms the essentially non-polar character of the FEP polymer. H-film is a polar material but between 300C and 23C its dielectric constant also steadily increases. Below 23C the rather significant decrease in dielectric constant can be explained by a dissipation factor peak which must occur below room temperature. The small but significant decrease in dielectric constant with increase in frequency, which is observable for H-film at every temperature except -269°C confirms the polar nature of the material.

The dissipation factor of FEP and H-film at room and low temperatures is plotted as a function of frequency at room and at low temperatures in Figure 1. The vertical bars show maximum and minimum values and at very low values of dissipation factor, it is not surprising that considerable variability is found since the limits of measurement sensitivity are being approached. It is noteworthy that a fairly strong absorption peak occurs with FEP Teflon between room temperature and -196°C. The effects of dielectric absorption are still very evident from the changing tan δ* at -269°C. The slope of this curve would indicate that another absorption peak occurs below -269C (4.2K) and if true it is remarkable. It would be most fruitful to make more measurements at intermediate temperatures and over a wider range of frequencies. Unfortunately, no apparatus capable of expanding the frequency range under these conditions is known.

It is important to note that tan δ of FEP is higher at -196°C than it is at room temperature. The same is almost true of H-film indicating that an absorption peak has occurred between room and -196°C. Since the curves for H-film are so flat at -196 and -269, it is difficult to conjecture about absorption peaks in this range. It may be only that ionic conductivity decreases markedly as temperature is decreased.

Figures 2, 3, 4 and 5 extend the data to temperatures above room temperature. In Figure 2 average values of tan δ for FEP are plotted without indicating the variation so as to avoid confusion. At the higher temperatures variability is much reduced, so in Figure 3 the results plus the range at 23 and 60C, for which variability is greatest, are plotted. It is interesting to note that variability is reduced and the value decreased after the specimen has been heated to 200°C. With so much variability it is unwise to attempt precise observations, but it does seem likely that moisture has some influence even on FEP Teflon. If the apparent moisture effects are discounted in Figure 2 by eliminating the results at 60C and at 23C before heating, it would then appear that a very small, broad absorption peak is found for FEP between 150 and 200C.

From Figure 4 it would seem as if two minor absorption peaks occur for H-film - at 100C and between 200 and 250°C. (The range of values is so small

*A careful calculation has indicated that this change cannot be caused by series resistance error.

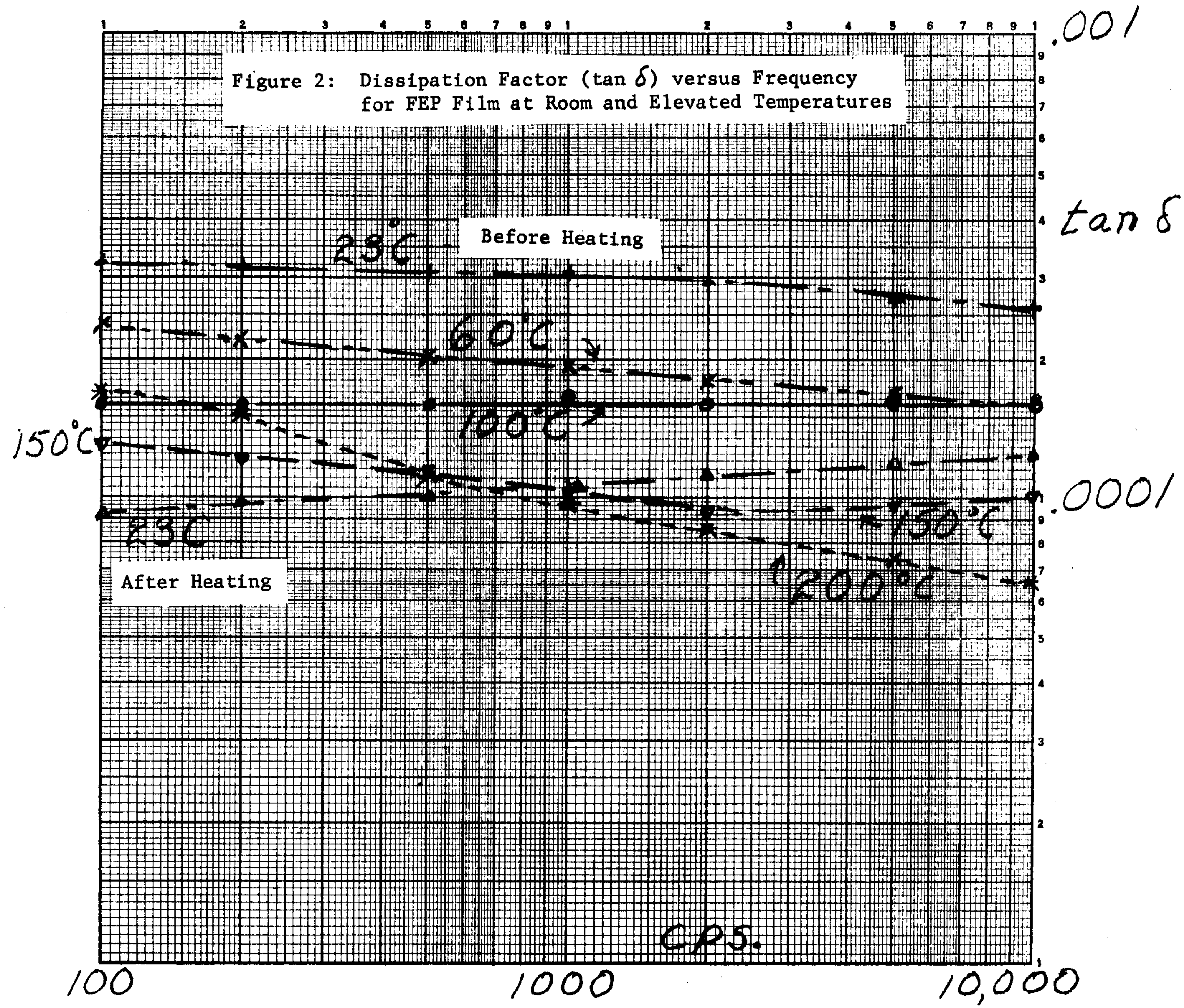


Figure 2: Dissipation Factor (tan δ) versus Frequency
for FEP Film at Room and Elevated Temperatures
Before Heating
After Heating
23°C
60°C
100°C
150°C
23C
150°C
200°C
.001
tan δ
.0001
100
1000
10,000
CPS.

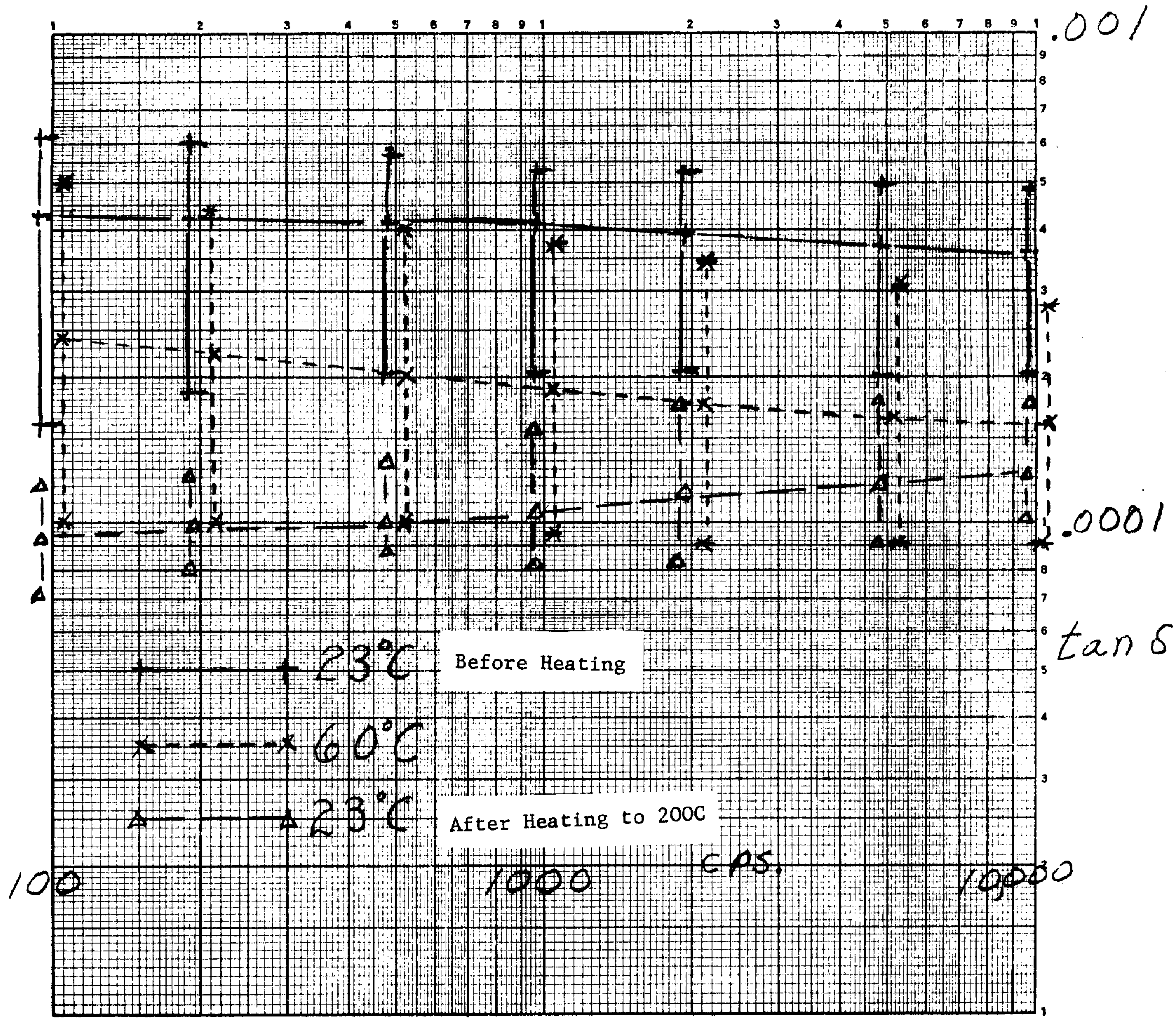


Figure 3: Dissipation Factor (tan δ) versus Frequency for FEP film - Vertical bars indicate range of test values

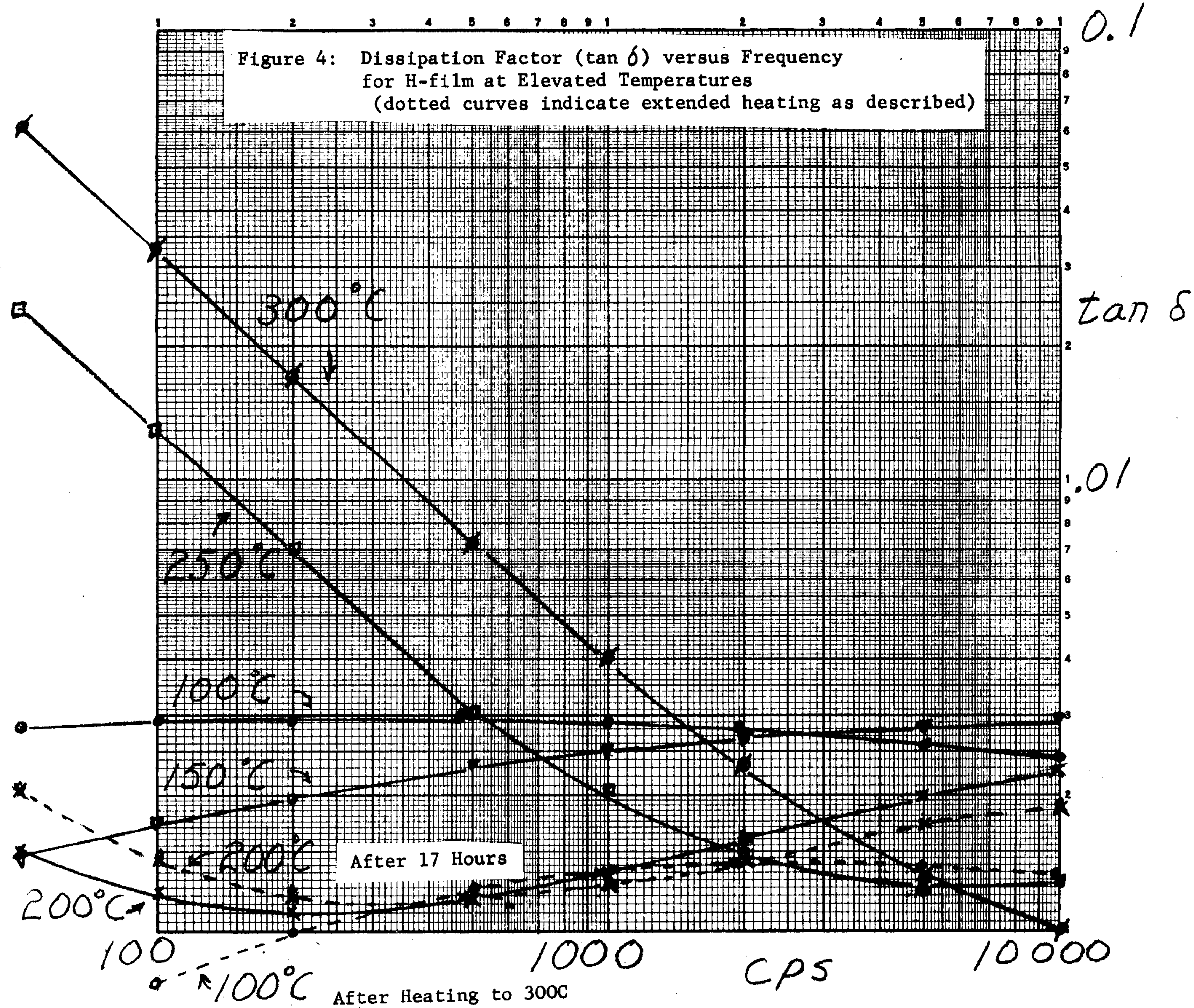
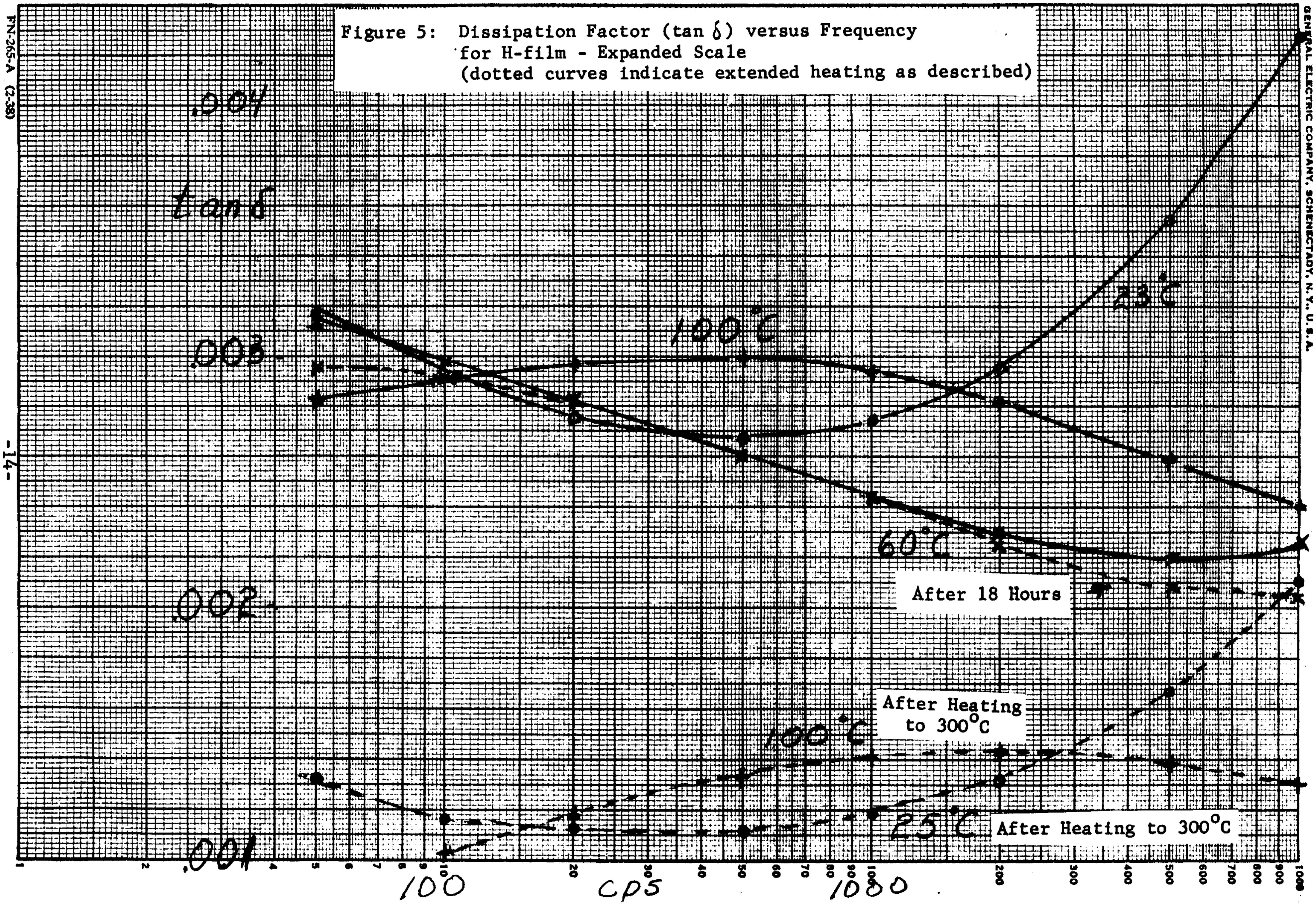


Figure 4: Dissipation Factor (tan δ) versus Frequency for H-film at Elevated Temperatures (dotted curves indicate extended heating as described)

Figure 5: Dissipation Factor (tan δ) versus Frequency
for H-film - Expanded Scale
(dotted curves indicate extended heating as described)



that it need not be plotted). At 250 and 300C the relatively high values at low frequencies indicates loss due to ionic conduction. In Figure 4 the dotted curves are used to show the long term effect of heating and in Figure 5 these results at low temperatures are plotted on an expanded arithmetic scale. From Figure 5 it is apparent that heating at 60C has only a small effect. In contrast, heating to 300C has a very marked effect in reducing the values at 100C and 23 (25)C without changing the shape of the curves. It would be easy to ascribe these changes to the loss of tenaciously held moisture except for the relatively small change in 17 hours at 200C, as shown in Figure 4. In consequence, molecular arrangement at 300C cannot be ruled out and perhaps incomplete polymerization or "cure" is indicated.

Again it is apparent that additional useful information could be obtained, particularly by investigating the effect of moisture exposure. Such work, however, is beyond the scope of the subject program.

Tests on Round Cable

In the tenth and eleventh quarterly reports, ten different insulation constructions for 19 strand #16 AWG were evaluated. From this work it became apparent that ML film coating on the individual wires and H-film lapped tape over the stranded bundle offered the best compromise properties for application at cryogenic temperatures. The results can be summarized briefly.

1. ML enamel has outstanding cryogenic flexibility and requires the minimum space.

2. H-film taping provides positive spacing and good electric strength over the stranded bundle with good flexibility at cryogenic temperatures.

3. An untreated HT-1 (polyimide) fiber braid provides better abrasion resistance than glass fiber, good resistance to aging at high temperatures and excellent flexibility at cryogenic temperatures.

According to the contractual requirements 1000 feet, each of 19 strand #16 AWG and 7 strand #26 AWG cable was made combining the three foregoing materials. The HT-1 braid was used to provide spacing with protection against the external metal shielding braid. Recognizing that the HT-1 braid was somewhat bulky and might absorb or wick liquid water, shorter lengths of two additional cables without the HT-1 braid were made. The construction of the four round wires evaluated in the last quarter are described in Table II. All of the round wires were made at Lowell, Mass. by General Electric's Wire and Cable Dept., under the capable direction of P.O. Nicodemus, The cryogenic flexibility and dielectric characteristics are reported below under separate headings.

Cryogenic Flexibility

All four cables described in Table II can be flexed repeatedly at room temperature with only a slight indication of opening in the H-film taping. In order to produce the maximum bend, the external shield and HT-1 braid were removed before test. Under this condition it was feasible to bend the #16 cable around a 1/4 inch mandrel and the #26 cable could be bent around a 1/8" mandrel.

In liquid helium, however, the H-film cracked as described in Table III. In the previous work, the #16 H-film taped sample was bent around a 3/4" mandrel without cracking. After thermal aging (and probably additional hydrolytic degradation) it exhibited only a few isolated cracks when bent about a 1½" mandrel. The reason for poor performance of the new #16 cable and the relatively poor performance of the #26 cable (only a little better than solid #16 with extruded Teflon, which fails on a 1" mandrel - see 8th Quarterly Report, July 15, 1963) was investigated. It was concluded, after careful examination, that the tension, pitch and the overlap with which the H-film tape had been applied were not responsible for the relatively poor cryogenic flexibility. It seems more likely that some unknown difference in the new sample of H-film may have been responsible. Such suspicions are increased by the evidence of hydrolytic degradation in the previous work and the evidence for possible moelcular rearrangement discussed in the previous section of this report. Moreover, considerable evidence has been gathered that inadequate cure in ML enamel (an aromatic polyimide polymer similar to H-film) is responsible for poor flexibility at cryogenic temperatures.

In contrast to the problems with the H-film, no cracking was encountered in the stranded ML coated wire when bent about a ½" mandrel, although the outer layer of H-film spalled off completely. Prior to the manufacture of the cable,problems had been encountered with cryogenic flexibility of the ML coated .0063 inch wire used for the seven strand #26 cable as described in Table IX of the 11th Quarterly Report. This wire, as originally made, had cracked on a 0.125 inch mandrel in liquid nitrogen. After it was subjected to additional baking, it could be bent around an .030 inch mandrel without failure. In Table III it is noted that isolated electrical failure in mercury was encountered in the strands of the #26 wire after bending. As will be described more fully later, such failures are due to electrical discontinuities in the wire which are present before the specimen is flexed. The excellent cryogenic flexibility of the ML enamel constitutes one of the strongest reasons for its use.

Voltage Breakdown

Four of the preliminary #16 round cable samples were insulated with H-film taping but with no underlying ML film. Voltage breakdown values for 10 foot specimens between conductors and shield were very variable.

at 23C, 50% RH	from 732 to 7304 volts
in liquid helium at -269°C	from 2300 to 5350 volts

Such variability is understandable in a nominal half lapped taped structure since the actual overlap will vary. Results for the new samples are given in

TABLE II

Construction of Round, Stranded Wire

Round Wire Code No.	Part	Description	Diameter (in.)
639-1	Conductor	#16 (19/.0113 HML)[1]	.062 - .064
	Insulation	H-film wrap	.068 - .069
	Insulation	HT-1 braid	.082 - .083
	Shield	.0057" silver copper	.102 - .104 (overall)
639-2	Conductor	#16 (19/.0113 HML)[1]	.063 - .065
	Insulation	H-film wrap	.068 - .070
	Shield	.0057" silver copper	.090 - .091
639-3	Conductor	#26 (7/.0063 HML)[2]	.0213 - .0217
	Insulation	H-film wrap	.0278 - .0290
	Insulation	HT-1 braid	.0396 - .0405
	Shield	.0057" silver copper	.0615 - .064
639-4	Conductor	#26 (7/.0063 HML)[2]	.0212 - .0214
	Insulation	H-film wrap	.028 - .030
	Shield	.0057" silver copper	.049 - .051

(1) Nominal .0113 copper with measured diameter .0127 avg.

(2) Nominal .0063 copper with measured diameter .0072 avg.

TABLE III

Flexibility in Liquid Helium
Stranded Round Cable
(10 Reverse Bends over ¼ to 1 3/4" mandrels in ¼" steps)

Cable No.	Mandrel Diameter (In.) and Remarks
639-2 (#16) Without HT-1 braid, shield removed	H-film cracks and loosens on 1 3/4" mandrel. ML enamel on wire passed 500 volt test in mercury after bending about ¼" mandrel.
639-4 (#26) without HT-1 braid shield removed	H-film loosened slightly, but does not crack on 3/4" mandrel. H-film cracks on ½" mandrel. ML enamel generally passed 500 volt test in mercury after bending about ½" mandrel but occasional failure encountered (see text).

Table IV. It is apparent that the voltage breakdown values for both #16 cables (693-1 and 639-2) are in the center of the range for the earlier results with less variability. It would appear that the newer cables have been taped more uniformly. The voltage breakdown values for the #26 samples (639-3 and 639-4) from conductor to shield are relatively very high. It is believe that the 2/3 overlap in the taping is responsible for the higher value. Since very little additional thickness results, the additional overlap is technically merited. The generally higher (with one set of exceptions) values in liquid helium can be explained by the slightly higher breakdown voltage of liquid helium as compared to air. Moreover, even after severe exposure to high humidity the values of breakdown voltage are still quite high. It should be added that all of the voltage breakdown values are higher than may be needed in the intended applications.

In order to study the variability in the breakdown voltage of the H-film taping in somewhat more detail, the shield and HT-1 braid were removed from 1 foot long samples. These specimens were immersed in mercury at room temperature. The results are plotted in Figure 6 on normal probability paper. The startling uniformity of breakdown voltage values for cable #639-3 emphasizes once again the advantage of the 2/3 overlap in the taping. The steep curve for sample #639-1, however, might give some cause for concern in that the minimum breakdown voltages might be very low. However, in making DC resistance tests 500 volts was applied between conductors and shield to all 1000 feet of samples #639-1 and 3 and to 200 feet of samples #639-2 and 4 (no HT-1 braid) without a single failure.

The same type of DC voltage withstand test was used to evaluate the voltage capability of the ML enamel wires in the stranded bundle. A potential of 100 volts was applied first and if no failure resulted, then 500 volts was applied. Each wire was tested to all the others. No failures at 500 volts were obtained in 1000 feet of the 19 strand cable #639-1, in 200 feet of 19 strand cable #639-2 and 200 feet of 7 strand cable #639-4. However, one conductor out of 7 failed at 100 volts in cable #639-3 and another of the 7 failed at 500 volts. Voltage breakdown tests cannot be made on more than one ML insulated conductor in the bundle because the failure affects more than one wire. It becomes necessary, therefore, to make only one breakdown test per specimen. Results for 1 foot long specimens are plotted on Gaussian probability paper in Figure 7. It is apparent that the #26 7 strand cable is significantly infereior to the #16, 19 strand cable. In order to study the situation in more detail, all of the insulation (except the ML enamel) was removed from 1 foot samples of #639-1 and #639-3. The bundle of ML insulated wires were then immersed in mercury and tested by applying voltage between all of the wires and the mercury with the results shown in Figure 8. Three of the specimens of #639-3 were shorted (failure at 0 volts). The remainder of these specimens failed at 100 volts or less, indicating that cracks or discontinuities were present in at least one wire of the seven in every single one foot specimen. However, the performance of sample #639-1 is much superior. Although considerable variability in breakdown voltage exists, it is evident that not a single crack or discontinuity is to be found in any of the <u>19</u> strands of nine, one foot long specimens of cable #639-1. The "day and night" difference between the two would indicate that either the stranding of the 7 strand #26 cable imposed more mechanical abuse than the stranding of the 19 strand #16 cable or that the wire used in the #26 strand had initially many more faults or discontinuities along its lenght. The latter situation seems much more plausible. It is evident that great

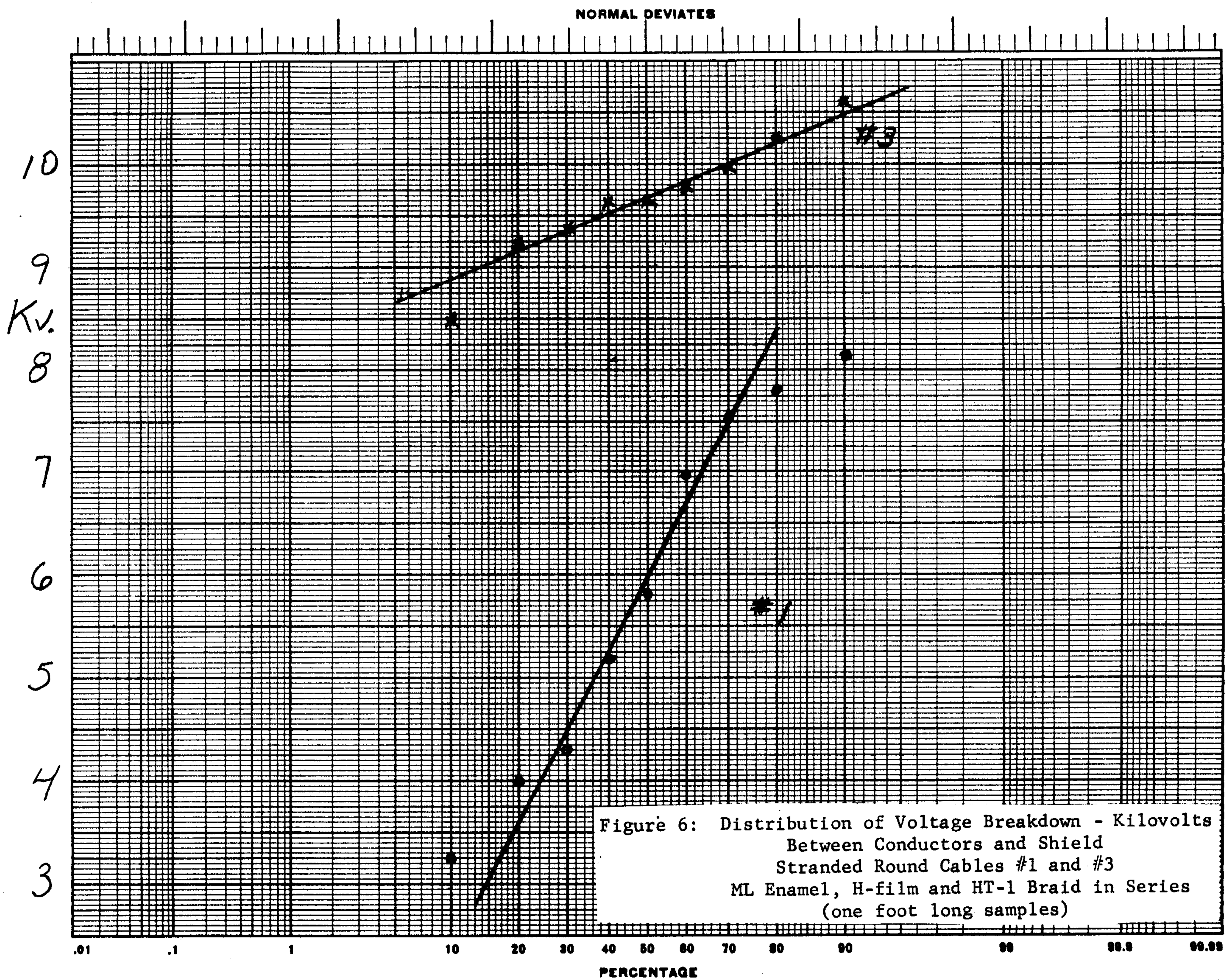
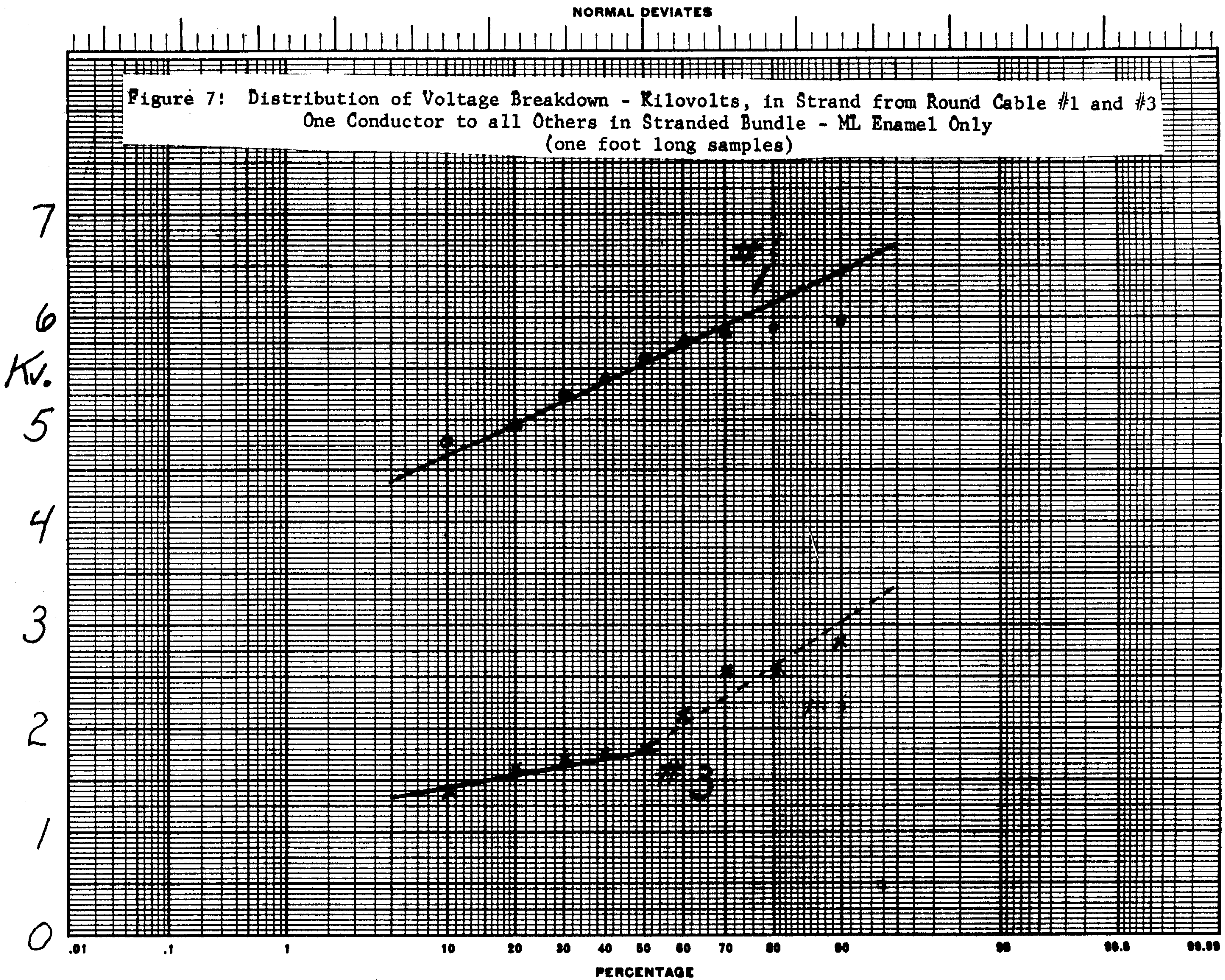


Figure 6: Distribution of Voltage Breakdown - Kilovolts
Between Conductors and Shield
Stranded Round Cables #1 and #3
ML Enamel, H-film and HT-1 Braid in Series
(one foot long samples)

Figure 7: Distribution of Voltage Breakdown - Kilovolts, in Strand from Round Cable #1 and #3
One Conductor to all Others in Stranded Bundle - ML Enamel Only
(one foot long samples)



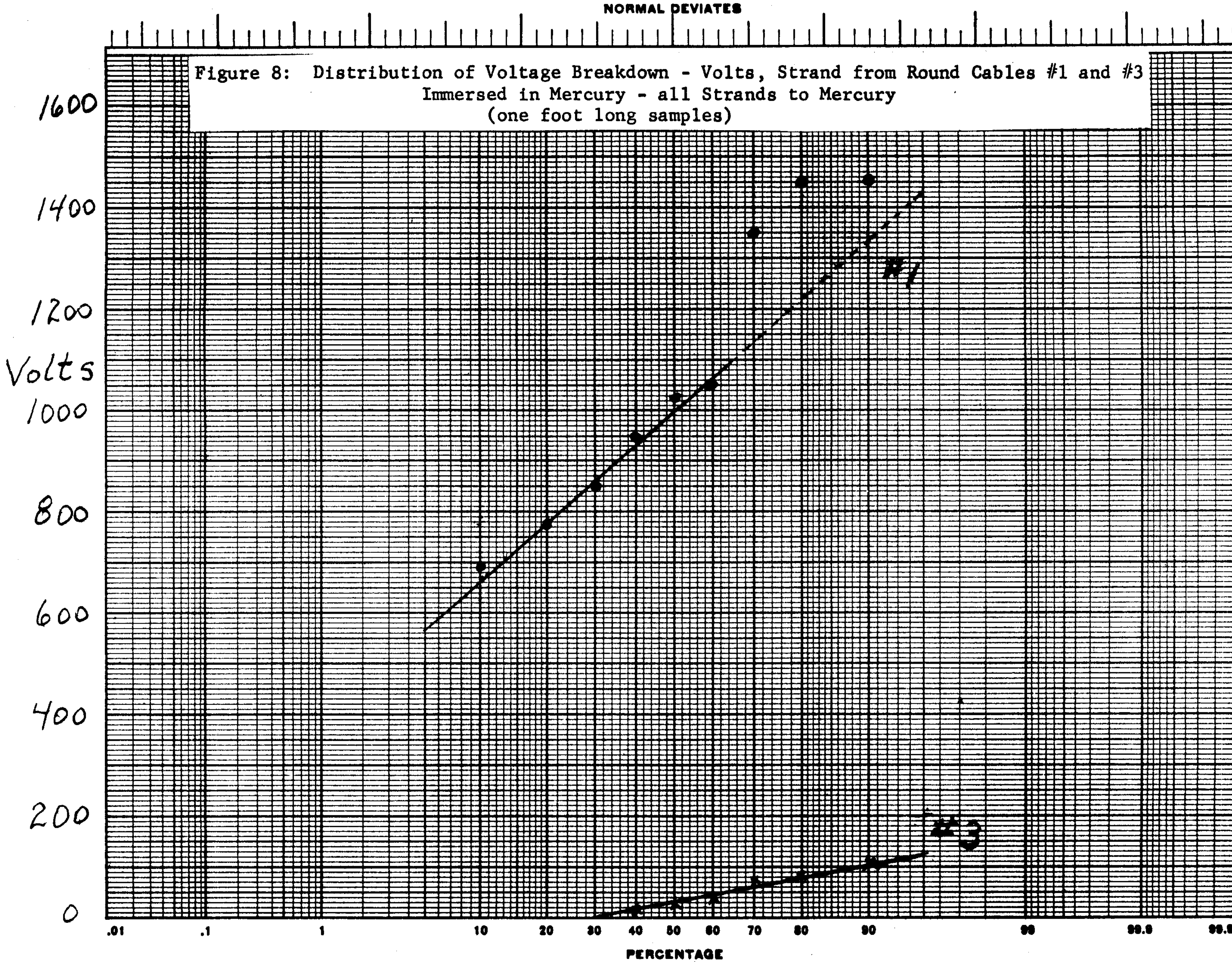


Figure 8: Distribution of Voltage Breakdown - Volts, Strand from Round Cables #1 and #3 Immersed in Mercury - all Strands to Mercury (one foot long samples)

TABLE IV

Voltage Breakdown - Stranded Round Cable

(10 foot lengths)

Cable #	Air 23C - 50% RH	Liquid Helium -269C		144 Hours at 23C - 100% RH
639-1 (#16)	2400	3400		1330
	2660	3500		1660
	2670	4100		2450
	2577	3667	Avg.	1813
639-2 (#16)	3780	3200		1620
(without HT-1 braid)	5780	3200		2490
	7790	3800		2900
	5780	3400	Avg.	2303
639-3 (#26)	10080	9800		7200
	10380	13000		7728
	10460	13200		7884
	10307	12000	Avg.	7604
639-4 (#26) (without	7360	9100		6348
HT-1 braid)	8140	10000		6588
	8800	10500		--
	8100	9870	Avg.	6468

care needs to be taken in achieving a low fault count if ML film coated wire is to be used for the purposes intended in this program. Nevertheless, even with a high fault count the faults are not likely to register between conductors as can be noted by a comparison of results for cable #639-3 in Figures 7 and 8.

DC Resistance

Insulation resistance measurements were made after 1 minute with 500 volts between all conductors and shield, as reported in Table V. It is interesting that results for a ten foot specimen cut from and compared to the longer samples are very similar. In fact, all the values, except for those after humidity exposure, are remarkably similar.* Attempts were made to measure the resistance of the 10 foot specimens while immersed in liquid helium at -269°C. While measured values were generally increased by a factor of about 100, it seemed evident from an analysis of the results that errors were involved and that the true values were actually much higher. Efforts have not yet been successful in overcoming difficulties with insulation resistance measurements at cryogenic temperatures.

Insulation resistance measurements have been made between each individual wire in the strand and all the others with results given in Table VI. Again, all values are remarkably similar. It is interesting that the poor continuity of the conductors in cable #639-3 (and probably cable #639-4) is not shown in these insulation resistance values. Unfortunately, measurements would be difficult and were not made after exposure at 100% RH.

Values for the change in resistance at 500 volts as a function of time on a single wire to all others in the strand is shown in Figure 9. The marked increase (polarization) is interesting. Even much greater polarization seems to occur at cryogenic temperatures and such changes constitute one of the problems that make measurements difficult.

In summary, the insulation resistance of all the H-film wrapped cables and the ML enameled wires also is very high, but not as high as would be expected with extruded Teflon. For almost every application these values should be sufficiently high at cryogenic temperatues. No problem with insulation resistance should ever be expected.

Dissipation Factor and Capacitance

In Figure 10 dissipation factor between all wires and shield is plotted as a function of frequency at room temperature, -196 and -269°C for the four round stranded cables. The ML enamel, H-film and, for cables #1 and #3, the HT-1 braid are measured in series. In Figure 11 similar results are reported except in this case, measurements were made between one wire and all the other wires connected together. The results shown in Figure 10 and 11 are summarized in Table VII at one frequency - 1000 cps. In considering these results it is important to compare similar results for H-film as shown in Figures 1 and 5. The following observations seem pertinent:

1. In Figure 10 and Figure 11 all of the curves at room temperature have about the same shape as H-film (see Figure 5), but except

*An incipient failure of the 10 foot sample at 100% RH is indicated by the low value and, after several minutes of voltage application, an intermittent short resulted.

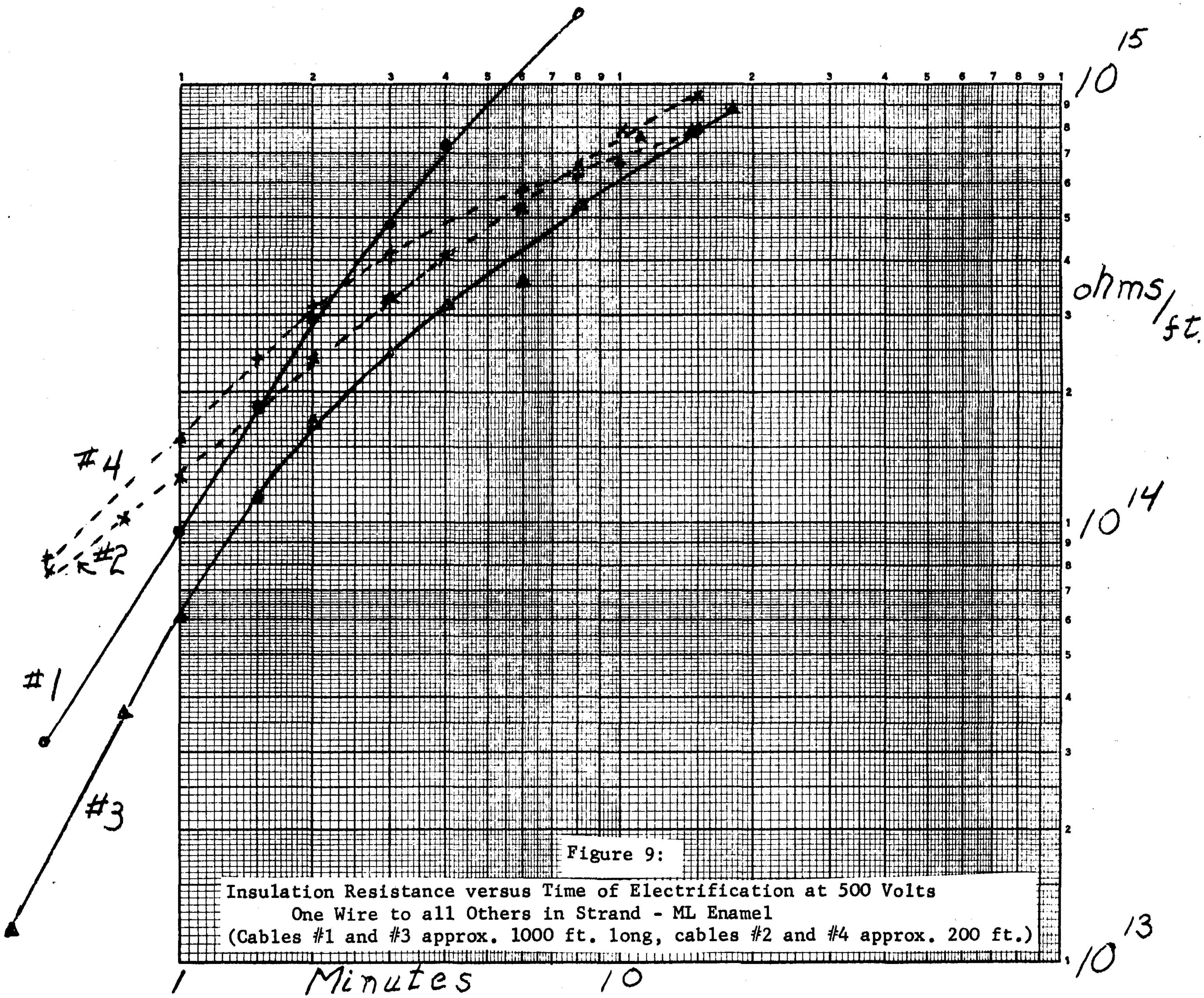


Figure 9:

Insulation Resistance versus Time of Electrification at 500 Volts
One Wire to all Others in Strand - ML Enamel
(Cables #1 and #3 approx. 1000 ft. long, cables #2 and #4 approx. 200 ft.)

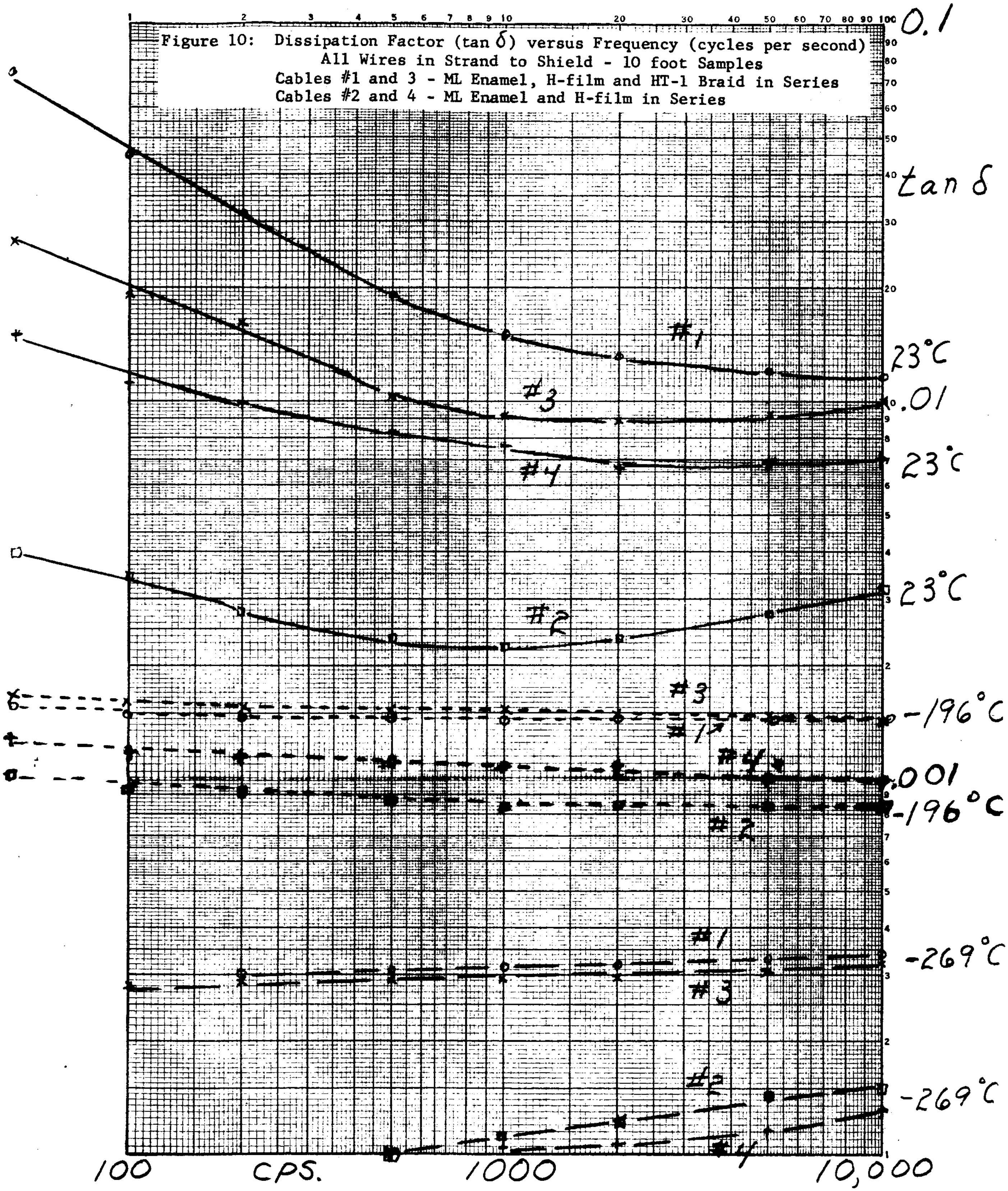


Figure 10: Dissipation Factor (tan δ) versus Frequency (cycles per second)
All Wires in Strand to Shield - 10 foot Samples
Cables #1 and 3 - ML Enamel, H-film and HT-1 Braid in Series
Cables #2 and 4 - ML Enamel and H-film in Series

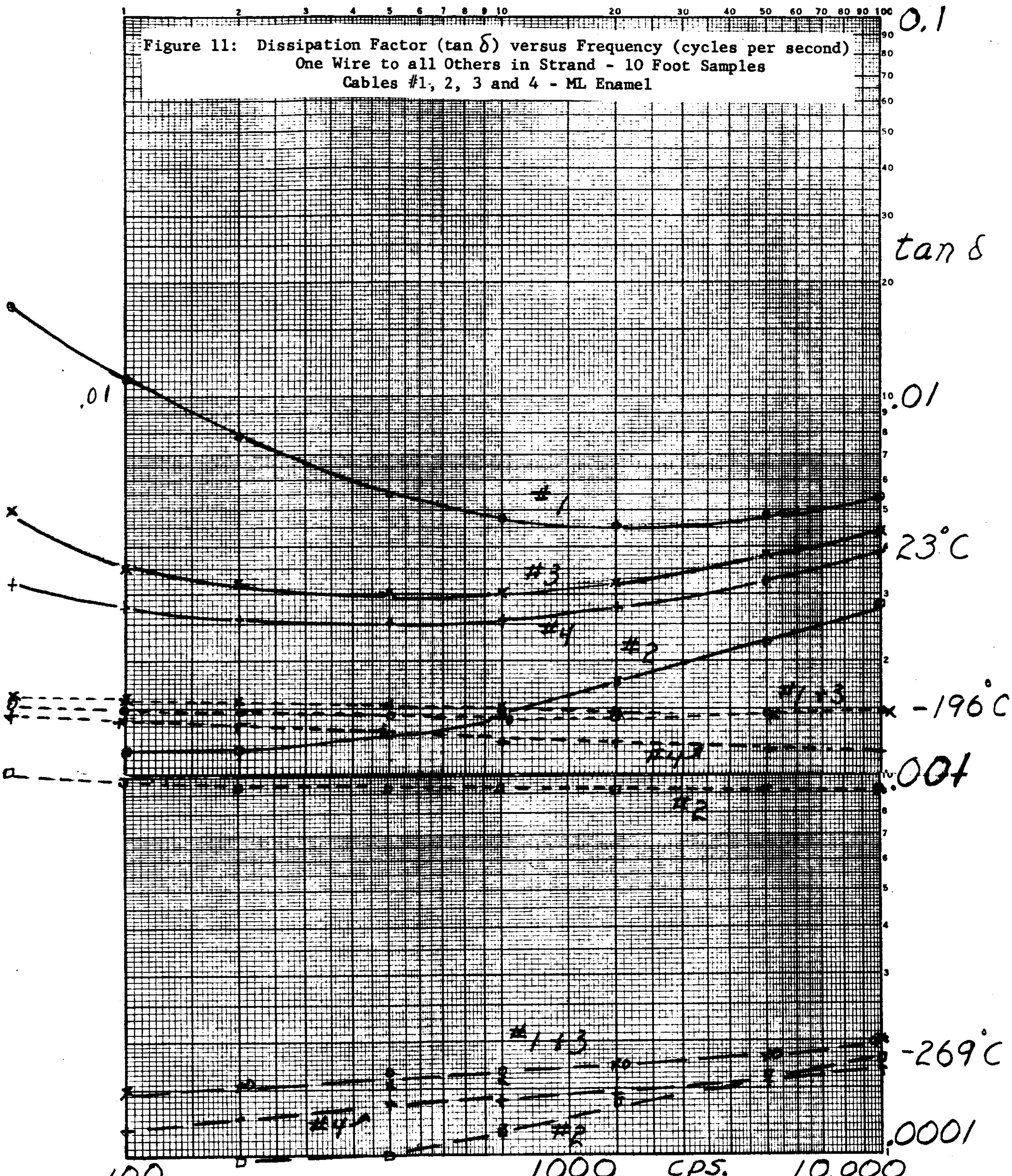


Figure 11: Dissipation Factor (tan δ) versus Frequency (cycles per second)
One Wire to all Others in Strand - 10 Foot Samples
Cables #1, 2, 3 and 4 - ML Enamel
0.1
tan δ
.01
.01
#1
23°C
#3
#4
#2
#1+3
-196°C
#4
.001
#2
#1+3
-269°C
#4
#2
.0001
100
1000
CPS.
10,000

TABLE V

Insulation Resistance - ohms/foot Length

(all wires in strand to shield at 500 volts)

AWG	Round Wire Code No.	HT-1 Braid	Long* Specimens at 50% RH -23C	10 Foot Specimens at 50% RH -23C	10 Foot Specimens after 144 hours at 100% RH -23C
#16	639-1	Yes	1.72×10^{13}	1.1×10^{13}	3.8×10^{11}
#16	639-2	No	2.6×10^{13}	1.3×10^{13}	2.5×10^{9}**
#26	639-3	Yes	1.1×10^{13}	3.0×10^{13}	7.1×10^{11}
#26	639-4	No	3.2×10^{13}	2.0×10^{13}	7.7×10^{11}

*639-1 and 639-3 were about 1000 ft. long, 639-2 and 639-4 about 200 ft. long.

**Intermittent short.

TABLE VI

Insulation Resistance - ohms/foot Length

at 23C - 50% RH

(one wire to all the others in the strand at 500 volts)

AWG	Round Wire Code No.	No. of Strands	Long Specimens* Avg.	Long Specimens* Max.	Long Specimens* Min.	10 Foot Specimens Avg.	10 Foot Specimens Max.	10 Foot Specimens Min.
#16	639-1	19	8.7×10^{13}	2.0×10^{14}	4.35×10^{13}	8.0×10^{13}	1.2×10^{14}	4.2×10^{13}
#16	639-2	19	8.8×10^{13}	1.3×10^{14}	6.1×10^{13}	5.4×10^{13}	1.2×10^{14}	2.0×10^{13} (2)
#26	639-3	7	6.7×10^{13}	7.4×10^{13}	5.6×10^{13} (1)	2.9×10^{13}	5.5×10^{13}	4.1×10^{12}
#26	639-4	7	1.3×10^{14}	1.5×10^{14}	8.4×10^{13}	6.5×10^{13}	1.5×10^{14}	2.8×10^{13}

*639-1 and 639-3 were about 1000 ft. long, 639-2 and 639-4 about 200 feet long.

(1) Two wires failed at 500 volts to the shield, 1 of these had failed at 100 volts.

(2) Two wires failed each to the other at 500 volts.

for cable #639-2, the values are higher for the cables, particularly at low frequencies.

2. If moisture or difference in cure are responsible for the variations in the magnitude of tan δ in H-film at 23C (see Figure 5), they may be similarly responsible for the variations in H-film taped cable as shown in Figure 10. Most likely, the ML enamel is involved also, since similar effects can be noted in Figure 11 in which the measurement involves primarily the ML enamel.

3. The HT-1 fiber braid appears to contribute to higher values of tan δ (cables #1 and #3 as compared to #2 and #4) particularly at the lower frequencies.

4. At -196°C tan δ values in Figure 10 are just a little lower than for H-film (see Figure 1). Very nearly the same results are obtained for ML enamel as shown in Figure 3 so that at -196°C ML enamel and H-film appear to have quite similar properties. The values for cables #1 and 3 with HT-1 braid are somewhat higher.

5. At -269°C the values of tan δ for cables #2 and #4 (without HT-1) in Figure 10 are lower than for H-film (Figure 1). The taping of H-film on the cable is laminated with interposed layers of helium liquid. This lower density of the taped structure probably explains the lower values. The decreasing values with decreasing frequency could be attributed to such a laminar effect.

6. The higher values for cables #1 and #3 (with HT-1 braid) at -269C suggest that the braid must have a higher loss. This observation is confirmed by the absence of a marked similar effect in Figure 11, where the braid should not and does not affect the values.

7. From a functional point of view these results confirm the other findings of this report in that the HT-1 braid serves no useful purpose and may be detrimental, particularly at room temperature.

8. From the two columns at the far right of Table VII, it is apparent that both high humidity and immersion in water adversely affect the dissipation factor. Nevertheless, these values are not as high as might be expected.

9. In final observation, the dissipation factor of the H-film taped cables (and of ML enamel) is higher than for Teflon, but lower than for many other conventional cable insulations - PVC for example, except perhaps after exposure to moisture. Dissipation factor peaks can be expected in the range of temperatures down to -196°C and even lower, but at liquid helium temperature, the loss is as low as that for Teflon at room temperature.

The changes in capacitance as a function of temperature and frequency for the round cables are relatively small and, therefore, less interesting than

TABLE VII

Dissipation Factor - Round Cable
at
1000 cps

AWG	Cable No.	HT-1 Braid	23C - 50% RH	$-196^{o}C$	-269C	After 144 hrs. at 100% RH	After 144 hrs. in water
			all wires to shield				
#16	639-1	Yes	.0149	.00143	.000313	.027	.066
#16	639-2	No	.00226	.00084	.000107	.084	-
#26	639-3	Yes	.00910	.00151	.000291	.022	.039
#16	639-4	No	.0070-.0084(?)	.00108	.000103	.036	.044
			one wire in strand to all others				
#16	639-1	Yes	.00470	.00108	.000170	.014	.033
#16	639-2	No	.00146	.00093	.000117	.033	-
#26	639-3	Yes	.00299	.00125	.000158	.038	.048
#26	639-4	No	.0025-.0029(?)	.00127	.000140	.015	.046

(?) - Variable results were encountered.

the changes in tan δ. Average values are summarized in Tables VIII and IX. A number of observations can be made.

1. Removing the HT-1 braid decreases the spacing and thereby increases the capacitance as would be expected.

2. The change in capacitance with change in frequency is largest at room temperature and particularly where the HT-1 braid is involved.

3. At low temperatures, only very small changes in capacitance result from frequency changes.

4. The properties of the ML enamel alone (data in the bottom section of Table VIII) are similar to those of the composite with H-film, (cables #2 and #4 in the top section of Table VIII).

5. Large changes in capacitance do occur at 100% RH or when immersed in water (see Table IX). The HT-1 braid has an adverse effect.

It may be useful here to review some of the precautions taken in making the AC measurements. (The problem is discussed more fully in the 10th Quarterly Report). The test specimen is shown in Photo 1. The 10 foot sample is looped back and forth on itself (not coiled) to eliminate inductance and its affect on the capacitance value. The series resistance of the outside metal shield is reduced to a minimum by soldering short circuiting wires across it as can be seen in the photograph. The internal conductor is connected at both ends to the measuring lead. The resistance of the measuring lead itself is kept below 0.1 ohms. With these precautions the error introduced for very low values of tan δ at the higher frequencies is eliminated.

Tests on Ribbon Cable

The construction of all of the ribbon cables are described in Table X. It should be recognized that shielded cables #4 and #5 were found in the earlier work to have inadequate voltage breakdown between conductors and shield. Moreover, this work did indicate that one shield should prove to be adequate. In consequence, the single shielded construction, cable #6, was developed. All of the ribbon cables have been made by Methode Inc., Chicago, Illinois.

On the basis of work described in the 10th and 11th Quarterly Reports, it has been concluded that cable #1 is the best unshielded construction. These data will not be repeated in full here since they are available in the earlier reports. However, the results on cable #6 are reported here for the first time.

Some additional dimensional measurements on Cable #6 are reported in Table XI. The ribbon cable tended to delaminate when aged for 60 days at 250^{o}C. After this very high temperature aging, the copper in both conductors and shield developed a black oxide coating. The FEP layer delaminated easily from the H-film. It was possible to peal away the copper shield fabric with a coating

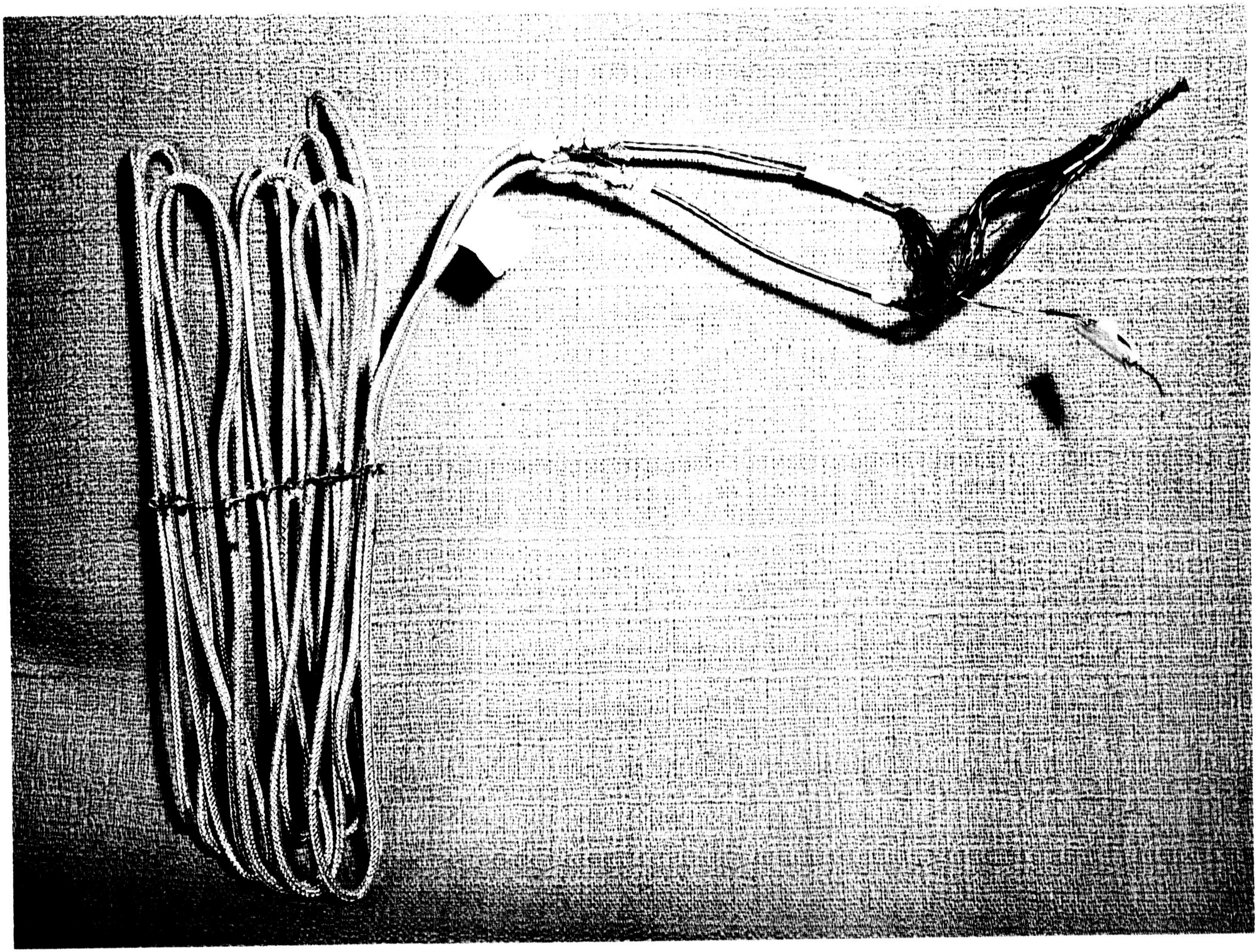


Photo 1: Test Specimen for Measurement of Dissipation Factor and Capacitance (note soldered shield and looped, not coiled construction) (ATL Photo 822901)

TABLE VIII

Capacitance - Round Cable

AWG	Cable No.	HT-1 Braid	Capacitance - p fds/ft. 1000 cps 23°C	-196°C	-269°C	% △ Capacitance 100 to 10,000 cps 23°C	-196°C	-269°C
					all wires to shield			
#16	639-1	Yes	111.36	108.26	93.65	6.50	0.43	.092
#16	639-2	No	191.89	202.4	177.28	0.81	0.32	.030
#26	639-3	Yes	55.17	53.60	46.99	2.5	0.44	.085
#26	639-4	No	71.73(?)	76.15	65.67	1.4(?)	0.25	.046
					one wire in strand to all others			
#16	639-1	Yes	90.72	87.75	80.94	1.4	0.72(?)	.047
#16	639-2	No	109.55	108.00	101.96	0.44	0.19	.039
#26	639-3	Yes	84.56	82.63	76.91	0.84	0.19	.061
#26	639-4	No	86.79(?)	85.14	78.31	0.69(?)	0.41	.033

(?) - Variable results were encountered.

TABLE IX

Change in Capacitance

(compared to 23^{o}C - 50% RH)

AWG	Cable No.	HT-1 Braid	p fds/ft. 23C-50% RH	% Δ at -196^{o}C	% Δ at -269^{o}C	% Δ after 144 hrs. 100% RH	in water
			all wires to shield				
#16	639-1	Yes	111.36	-2.7	-15.6	+233.	+319.
#16	639-2	No	191.89	+5.7	-7.6	+24.5	-
#26	639-3	Yes	55.17	-2.8	-14.9	+162.	+223.0
#26	639-4	No	71.73(?)	+6.4	-8.5	+39.2	+141.
			one wire in strand to all others				
#16	639-1	Yes	90.72	-3.3	-10.8	+40.0	+82.3
#16	639-2	No	109.55	-1.4	-6.9	+7.9	-
#26	639-3	Yes	84.56	-2.2	-9.1	+33.6	+70.0
#26	639-4	No	86.79(?)	-1.9	-9.8	+16.1	+80.0

(?) - Variable results were encountered.

TABLE X

Construction of Flat Ribbon Cable

(all dimensions in inches)

Ribbon Cable No.	Construction	Overall Width	Overall Thickness
#1 Unshielded	.002H + .002 FEP[(1)] film .004 thick x .040 conductor strip[(2)] .002 FEP + .002 H film	0.993	.0088
#2 Unshielded	.001H + .001 FEP film .004 thick x .040 conductor strip .001 FEP + .001 H film	0.993	.0062
#3 Unshielded	.001H + .001 FEP film .0027 thick x .040 conductor strip	0.985	.0062
#4 Shielded one side	.001H + .001 FEP film copper wire mesh (fabric shield) .001 FEP + .001H + .001 FEP film[(3)] .0027 thick x .040 conductor strip .001 FEP + .001 H film	0.985	.0115
#5 Shielded two sides	.001H + .001 FEP film copper wire mesh (fabric shield) .001 FEP + .001H + .001 FEP film .0027 thick x .040 conductor strip .001 FEP + .001H + .001 FEP film Copper wire mesh (fabric shield) .001 FEP + .001 H film	0.985	.0163
#6 Shielded one side	.001H + .001 FEP film Copper wire mesh (fabric shield) .002 FEP + .002H + .002 FEP film .0027 thick x .040 conductor strip .002 FEP + .002 H-film	0.990	.0137 to .0140

(Note 1) - The FEP (per fluoroethylene - propylene) film is extruded by du Pont directly on one side of the H (du Pont polyimide) film without adhesive or other bond. The FEP film is placed next to the conductors.

Note (2) - The twelve copper conductors are on a .075" centers (spacing).

Note (3) - Has FEP film adhered by extrusion to both faces of the H-film.

TABLE XI

Actual Measurements
Ribbon Cable #6 after Aging at 250C
(Dimensions in mils)

	Range	Avg.
H-film	0.84 - 0.96	0.90
Copper wire mesh + FEP Teflon		4.8
Copper wire mesh with FEP burned out		(4.6)
H-film	1.9 - 2.1	2.0
.0027 conductor + 2 layers FEP	4.5 - 4.8	4.65
Conductor alone (oxide layer removed on FEP)		(2.5)
H-film	2.0 - 2.1	2.05
Overall thickness	13.9 - 14.3	14.1

Note: Delamination occurred or was easily accomplished at the interface of the H-film and the FEP Teflon.

of FEP on each side which penetrated through the mesh. With a flame it was easy to remove the FEP, leaving just the copper shield fabric. The conductors likewise could be peeled away with a layer of FEP on each side which continued to hold them in position. It was then possible to peel the conductor "out of" its FEP encapsulation, leaving the black oxide adhering to the FEP layer. In this way it was possible to make actual measurements of the different laminar parts. Such measurements cannot be made before thermal aging because the tight adhesion is difficult to overcome.

Flexibility

Since flexibility at cryogenic temperatures functionally may be the most important property for such use, the flexibility of all the ribbon cable is reviewed in Table XII. Like all the rest, cable #6 does not crack on a ¼" mandrel in liquid helium so long as the cable is not bowed or twisted. Since the earlier ribbon cable samples had been unaffected by aging at 120°C, cable #6 was aged at 250C for 60 days. After this very severe thermal aging, not only delamination, but some embrittlement of the H-film in liquid helium is noted. At 23C, however, no cracking of the H-film occurred even with sharp creasing, although delamination did occur. Again it is apparent that test at cryogenic temperatures will detect effects of thermal aging before they become apparent at room temperature.

While the cryogenic flexibility of ribbon cable is remarkable, it is desirable once again to emphasize that cracking will occur if bowed or twisted ribbon cable is flexed at cryogenic temperatures. Unless materials with very much higher elongation at cryogenic temperatures are discovered or developed, this problem will persist. At any rate, the H-film laminates are superior to any other material yet investigated.

Voltage Breakdown

Ribbon cable #6 was developed primarily to overcome the problem of low breakdown voltage to the shield in cables #4 and #5 (see the 11th Quarterly Report). The extremes of these values are reviewed briefly below:

	Range at 23C	Range at -269C
Cable #4	240 to 5652 volts	84 to 5650 volts
Cable #5	>216 to 3744 volts	350 to 5050 volts

From the results for three, one foot long specimens, as given in Table XIII, it is apparent that the minimum value for cable #6 is greater than the maximum values for cables #4 and #5. Moreover, when cable #6 was tested in liquid helium, flashover was obtained before voltage breakdown except for just one conductor.

TABLE XII

Flexibility in Liquid Helium

Flat Ribbon Cable

(10 Reverse Bends over ¼" and ½" Mandrels)

Ribbon Cable No.	Mandrel Dia. (In.) and Remarks
1	OK ¼"
2	OK ¼"
3	OK ¼"
4	OK ¼"
5	Functionally Ok, but delamination occurs at edges and between external H-film and copper mesh shield on inside of ½" bend. Very minor delamination occurs with a ½" mandrel.
6	OK ¼"

Cables 1-5 - Aged 60 days at 120C - showed no change.

Cable 6 - Aged 60 days at 250C, OK 3/4", at 1/2" H-film on outside of shield cracked, at 1/4" shield fabric delaminated.

TABLE XIII

Voltage Breakdown - Ribbon Cable

(from conductor to shield)

Cable #6 at 23^{o}C - 50% RH

	A		B		C	
Breakdown Sequence	Cond. No.	Volts to Shield	Cond. No.	Volts to Shield	Cond. No.	Volts to Shield
1	10	8400	4	8592	1	9144
2	9	6480	9	8244	3	6396
3	8	7572	2	6336	2	7992
4	12	6600	12	6960	4	8892
5	1	9480	10	7800	9	7284
6	7	9252	11	9288	8	7644
7	4	8040	1	6696	11	8940
8	5	6800	5	7800	10	8256
9	3	6840	6	9240	6	8712
10	2	9000	3	7596	5	7500
11	6	8040	7	7416	7	7244
12	11	6840	8	6960	12	8556

PA - 7800 volts, 5% - 6000 volts, 95% - 9600 volts.

In liquid helium at -269^{o}C - specimen flashed over.

	A	B	C
Flashover	8300 volts*	7700 volts	8500 volts

*One failure at 8300 volts.

The 36 test results from Table XIII are plotted on normal probability paper in Figure 12 - a very expanded voltage scale has been used. It is apparent that the .002 in H-film in cable #6 has solved the voltage breakdown problem and low values of voltage breakdown are extremely unlikely.

Insulation Resistance

Insulation resistance after 1 minute at 500 volts has been measured on two specimens of #6 ribbon cable - 35 and 49 feet long. Results are reported in Table XIV. No attempt was made to guard the conductors at the end of the test specimen since such guarding would be difficult and would most likely introduce additional measurement problems. Since relatively long specimens were used, the error due to end effect should be minimal. Quite consistent results have been obtained, although for unknown reasons, measurements could not be made in liquid nitrogen. It is interesting that values for a single conductor out of the twelve are approximately 12 times the value for all conductors tied together as they should be. In liquid helium at -269^{o}C, the resistivity increased by a factor of 1000.

Resistivity as a function of time for one specimen has been plotted in Figure 13. The very marked polarization is interesting. In liquid helium such polarization is even more pronounced, but no quantitative measurements have been made. At cryogenic temperatures insulation resistance rather quickly rises to such high values that it can be measured with difficulty, if at all.

Dissipation Factor and Capacitance

It seems worthwhile in this report to repeat data obtained with the unshielded ribbon cables #1 and #2 since they represent the best and the worst of the unshielded ribbon cable. Figures 24 and 25 of the 10th Quarterly Report are reproduced here as Figures 14 and 15. In Figure 14 values of dissipation factor between two sets of adjacent conductors are reported. One set was located at the edge of the ribbon and the other at the center of the ribbon as noted. In liquid nitrogen and in liquid helium the values of tan δ lie between the values for H-film and FEP film, as shown in Figure 1. It should be remembered that the voltage stress is tangential to the planes in which the FEP and H-films are laminated together. At room temperature, relatively high values of tan δ have been obtained which peak in a frequency range from 100 to 200 cps. These room temperature measurements bear no resemblance to the volume characteristics for H-film, as shown in Figure 1

The changes in capacitance versus frequency, shown in Figure 15, should be compared with the associated values of tan δ in Figure 14. It is immediately apparent that the increase in capacitance at low frequencies can be correlated with the magnitude of the tan δ values, as would be expected from theoretical considerations. The large magnitude of the capacitance change, with one exception, would be best explained by the adsorption of moisture on surfaces. Since the external surfaces of the specimens is much the same, it seems likely that surfaces at the interface between the FEP and H-film are involved. Probably the character of the lamination is a factor. Cable #2, with thinner FEP film, appears to be more affected (less bond) as might be expected. AC measurements may provide an effective means for indirectly measuring the effectiveness of the lamination in ribbon cable.

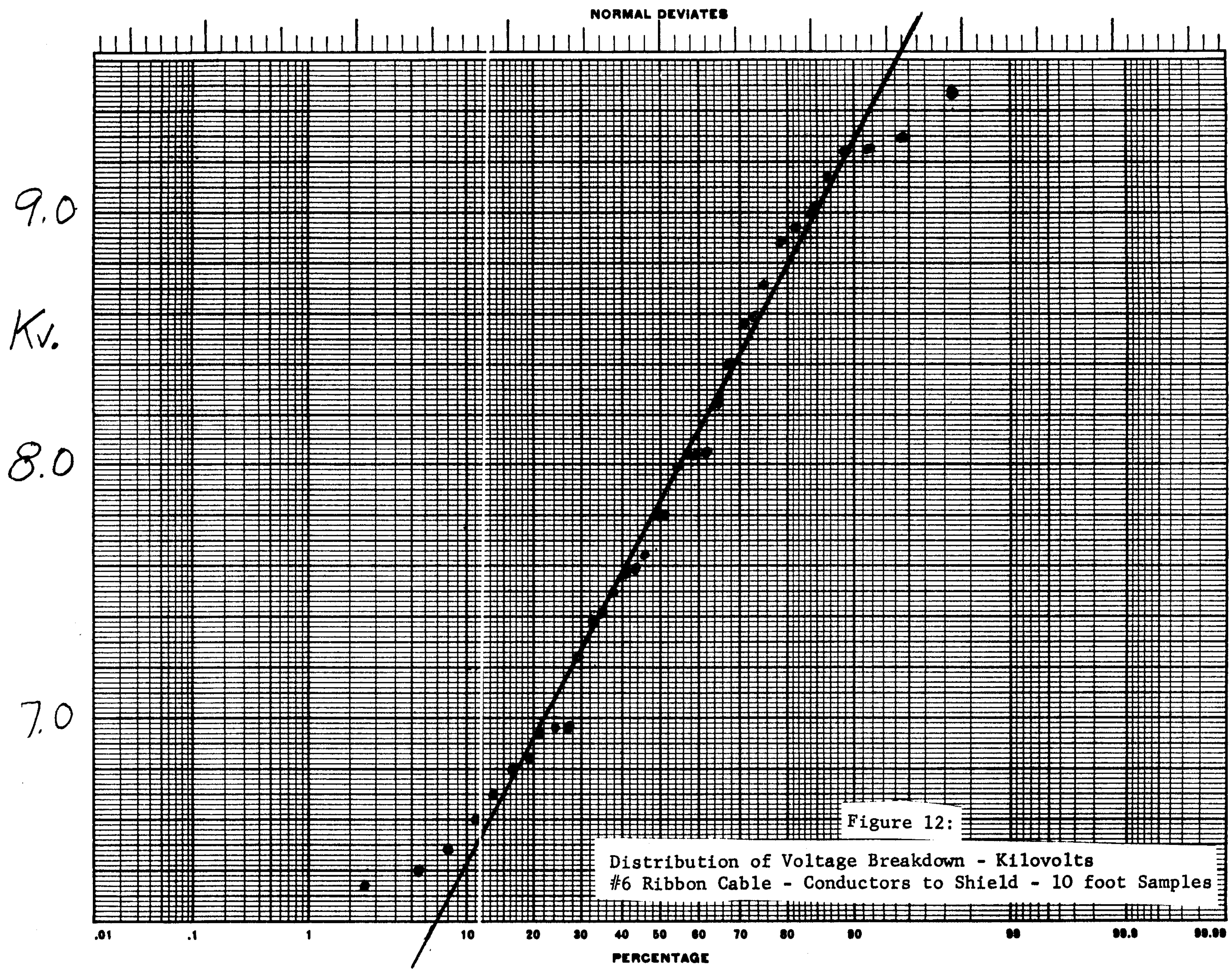


Figure 12:

Distribution of Voltage Breakdown - Kilovolts
#6 Ribbon Cable - Conductors to Shield - 10 foot Samples

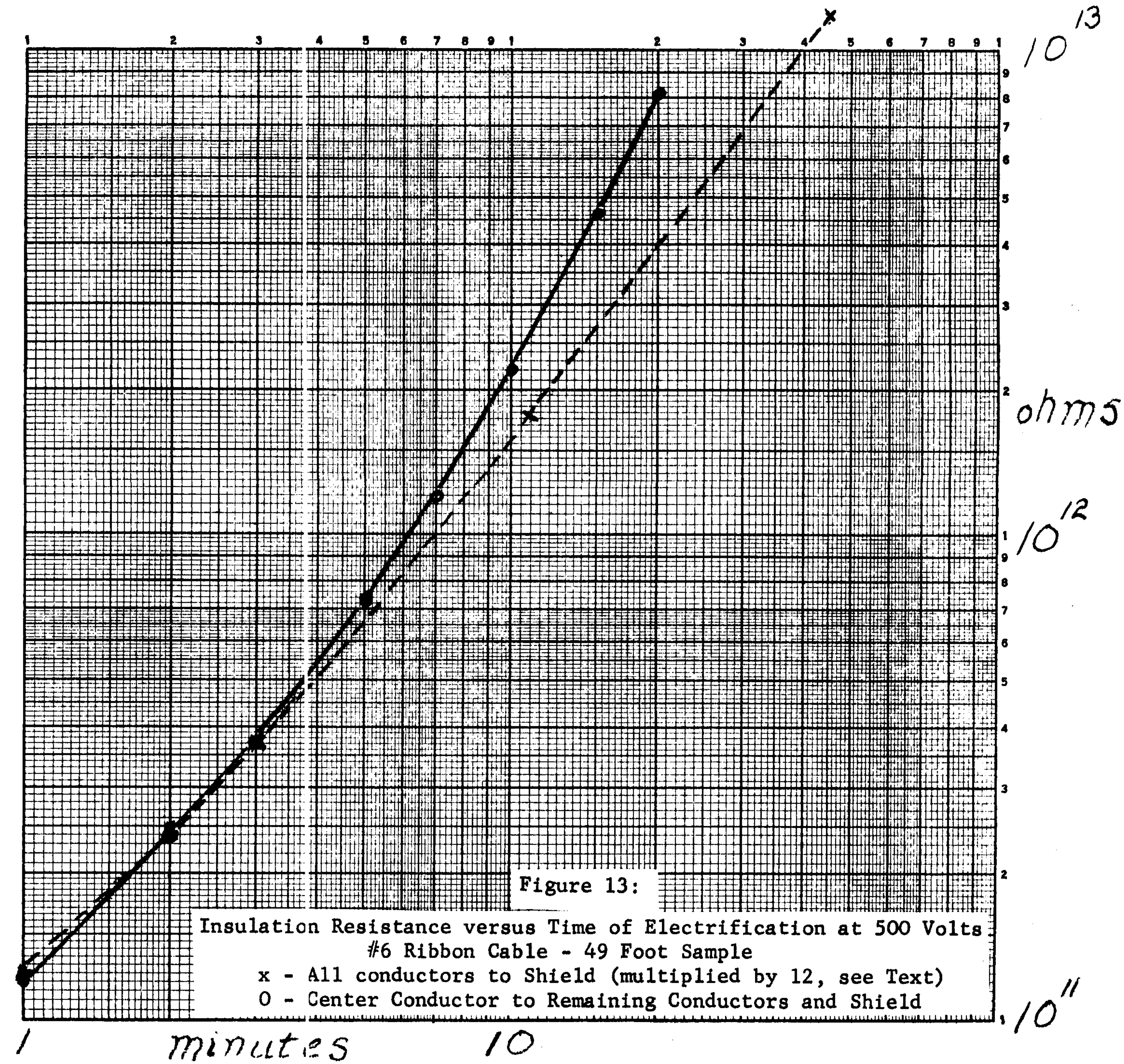


Figure 13:

Insulation Resistance versus Time of Electrification at 500 Volts
#6 Ribbon Cable - 49 Foot Sample
x - All conductors to Shield (multiplied by 12, see Text)
O - Center Conductor to Remaining Conductors and Shield

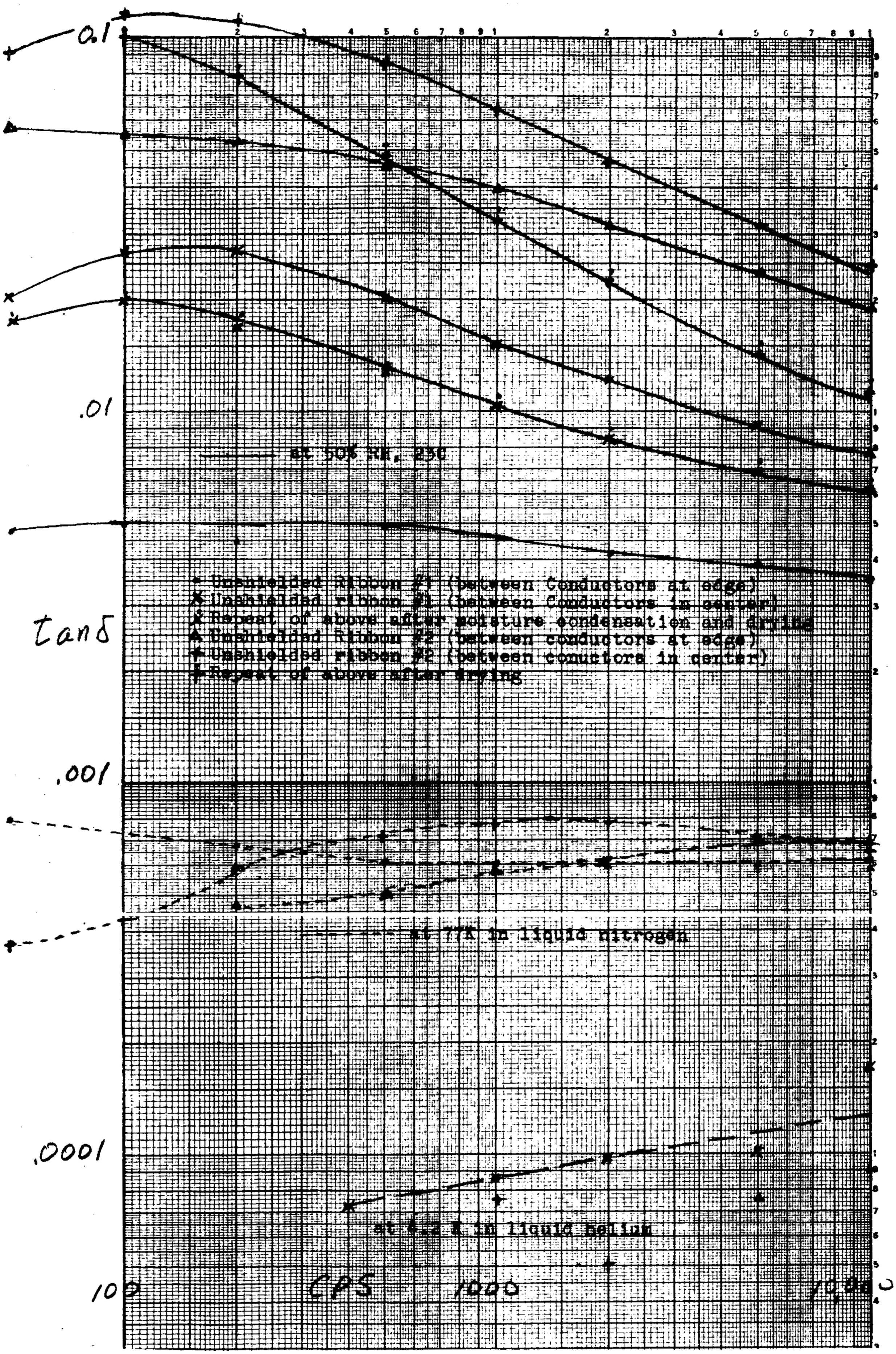


Figure 14. Dissipation Factor (tan δ) vs Frequency - Unshielded Ribbon Cables #1 and #2

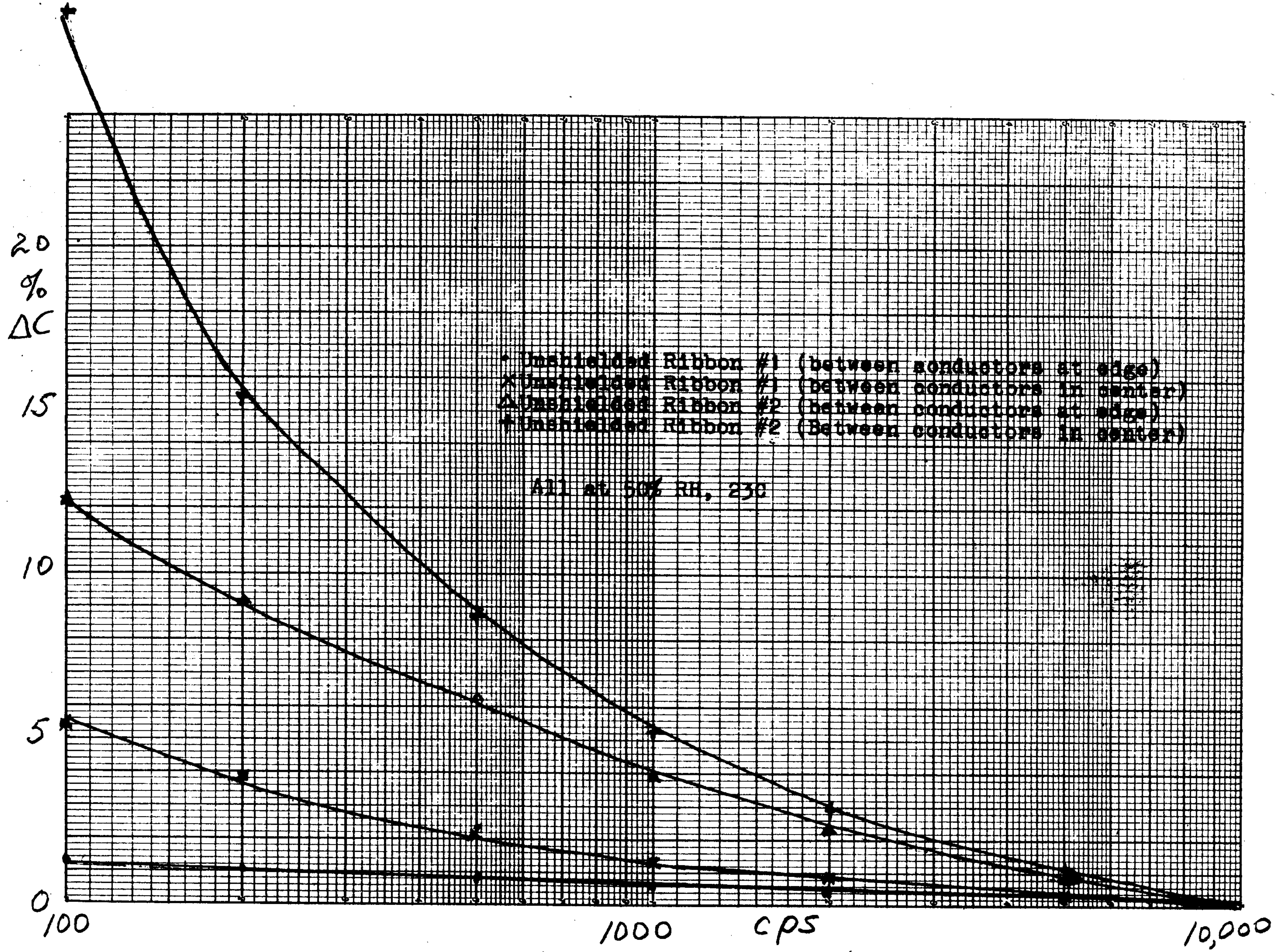


Figure 15. Change in Capacitance (Δ C) vs Frequency - Unshielded Ribbon Cables #1 and #2

TABLE XIV

Ribbon Cable #6

Insulation Resistance

ohms/foot

Connector	Specimen No.	23C	-196C	-269°C
All conductors to shield	1	4.2×10^{11}	Noise prevented measurement	5.4×10^{14}
	2	5.4×10^{11}		7.0×10^{14}
Center conductor to all else	1	4.2×10^{12}	Noise prevented measurement	9.6×10^{15}
	2	6.4×10^{12}		1.1×10^{16}
Outside conductor to all else	1	5.9×10^{12}	Noise prevented measurement	8.3×10^{15}
	2	4.6×10^{12}		7.0×10^{15}

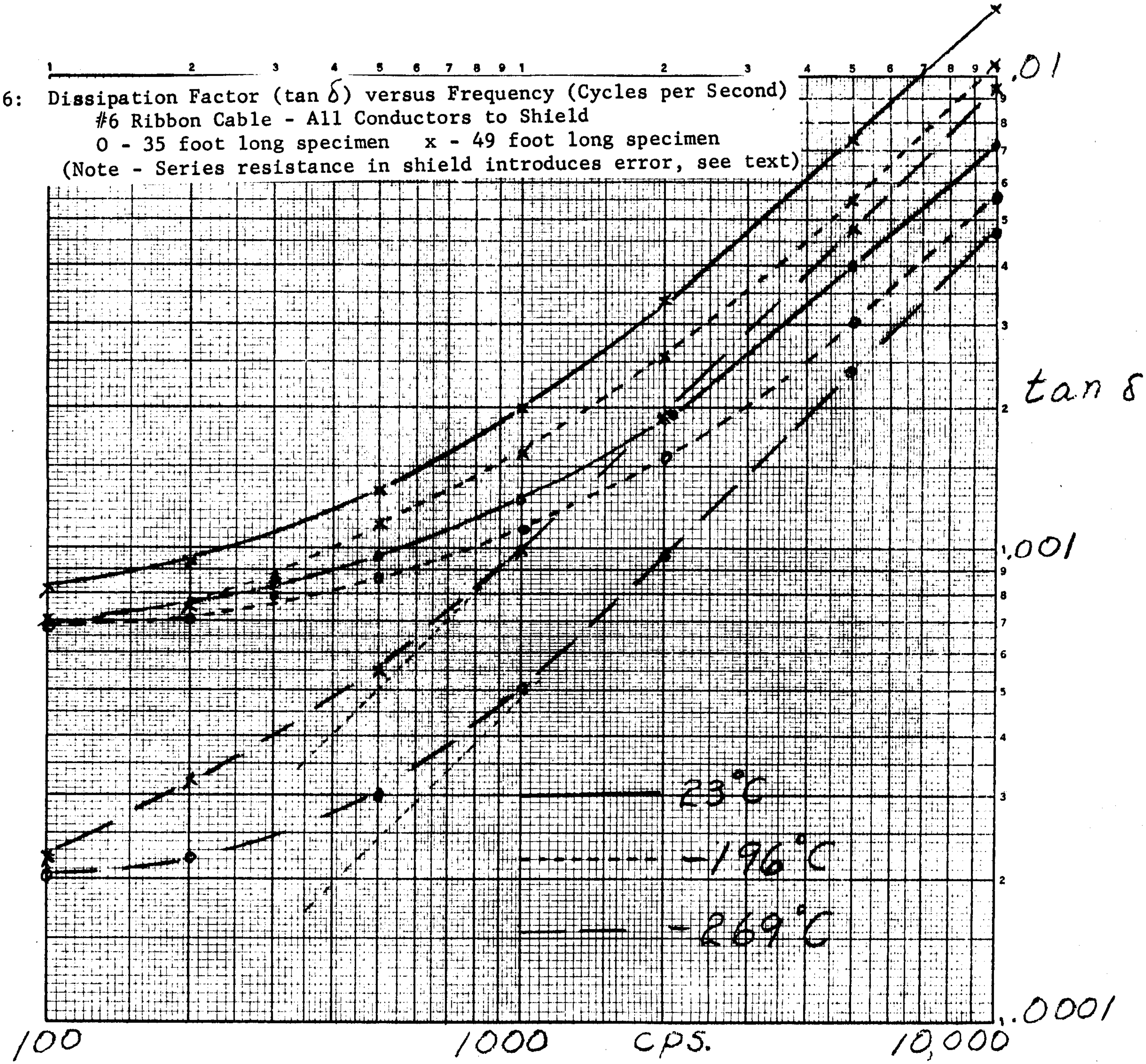
In Figure 16 values of tan δ between all the conductors (connected together) and the shield are reported for two cables - 35 and 49 feet long. Examination of these results, particularly those at -269°C leads to the conclusion that series resistance error may be involved. The measured DC resistance is compared to the calculated AC resistance in Table XV. In making these calculations, it has been assumed that tan δ is independent of frequency which is a reasonable, if not quite true, approximation. From the results in Table XV, the assumption of series resistance error at high frequencies appears to be quite plausible if distributed resistance in the shield is accepted as the reason. However, it is startling that the series resistance is so little affected by temperature. If the shield is made of a copper alloy rather than pure copper, the small change in resistance could be explained. It is possible, but less likely, that "skin" effects are involved. It is important to recognize how important the series resistance of the shield may be in determining the AC characteristics of ribbon cable. Once again an experimental error has led to useful information, but it is necessary that the correct explanation be available to explain the data obtained.

It should be noted here, that the tan δ values reported for ribbon cables #4 and #5 in the 10th Quarterly Report are also in error because of distributed resistance in the shield which appears as a series resistance in the measurement. This possibility was noted then for the results at -269°C, but the error contributed to the values at room and liquid nitrogen temperatures has just been recognized. Because the voltage breakdown of ribbon cables #4 and #5 is inadequate, the tan δ measurements will not be repeated.

It has been necessary to repeat the tan δ measurements for ribbon cable #6 with results shown in Figures 17 and 18. When these results for cable are compared with results for FEP and H-films, as shown in Figure 1, it is apparent that the expected values are obtained. The change in capacitance for the ribbon cable, as shown in Table XVI, is also essentially like that obtained with the films themselves. It is reassuring that the information obtained on the basic materials is reflected in the cables which contain them.

In summary, relatively low values of dissipation factor and quite constant values of capacitance versus temperature and frequency are found between conductors and shield for ribbon cable #6. However, some problems may occur in the values of tan δ and the change in capacitance between conductors as shown in the results for ribbon cable #1 and particularly ribbon cable #2. These problems appear to be overcome by developing adequate bond between laminations in the manufacture of the ribbon cable.

Figure 16: Dissipation Factor (tan δ) versus Frequency (Cycles per Second)
#6 Ribbon Cable - All Conductors to Shield
0 - 35 foot long specimen x - 49 foot long specimen
(Note - Series resistance in shield introduces error, see text)



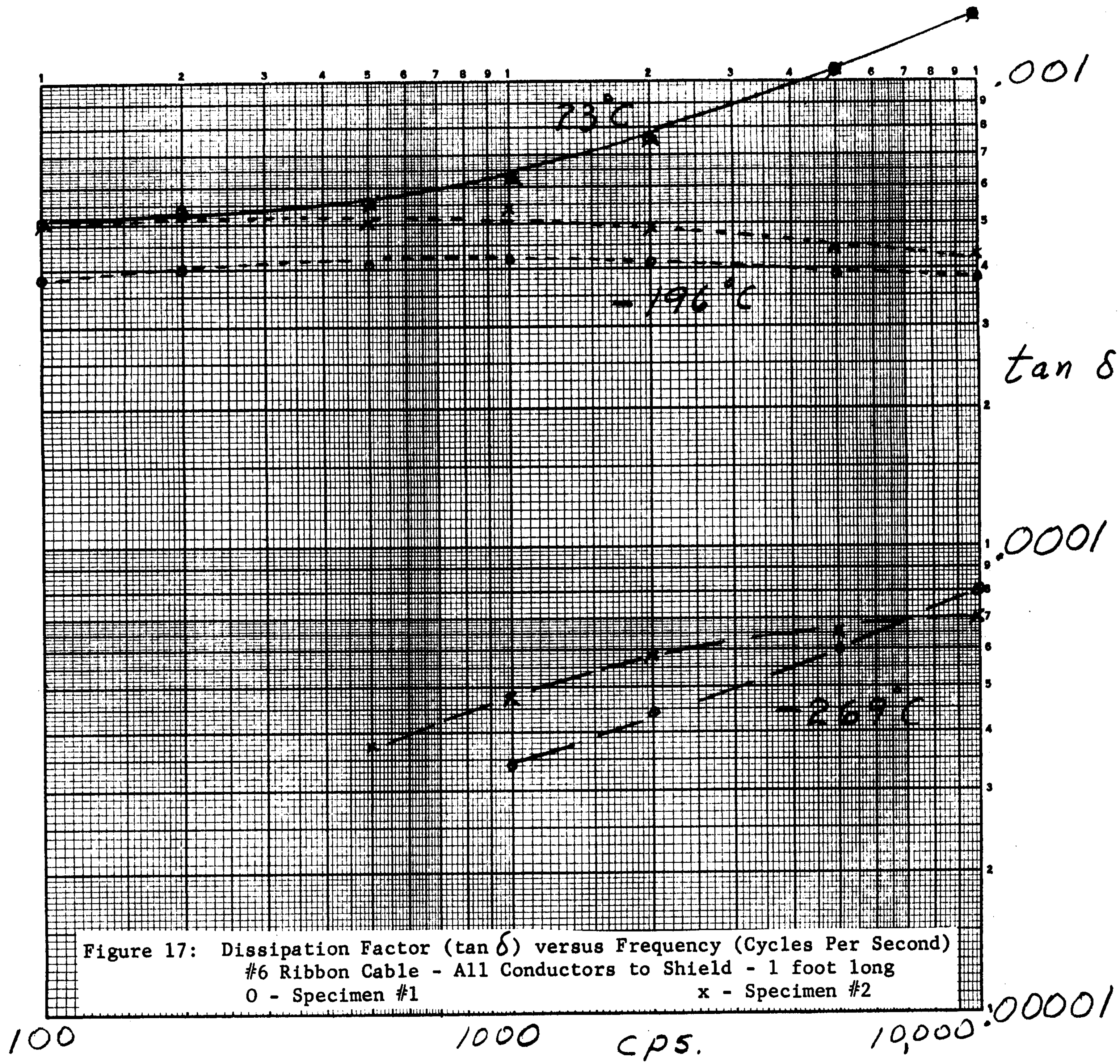


Figure 17: Dissipation Factor (tan δ) versus Frequency (Cycles Per Second)
#6 Ribbon Cable - All Conductors to Shield - 1 foot long
0 - Specimen #1 x - Specimen #2

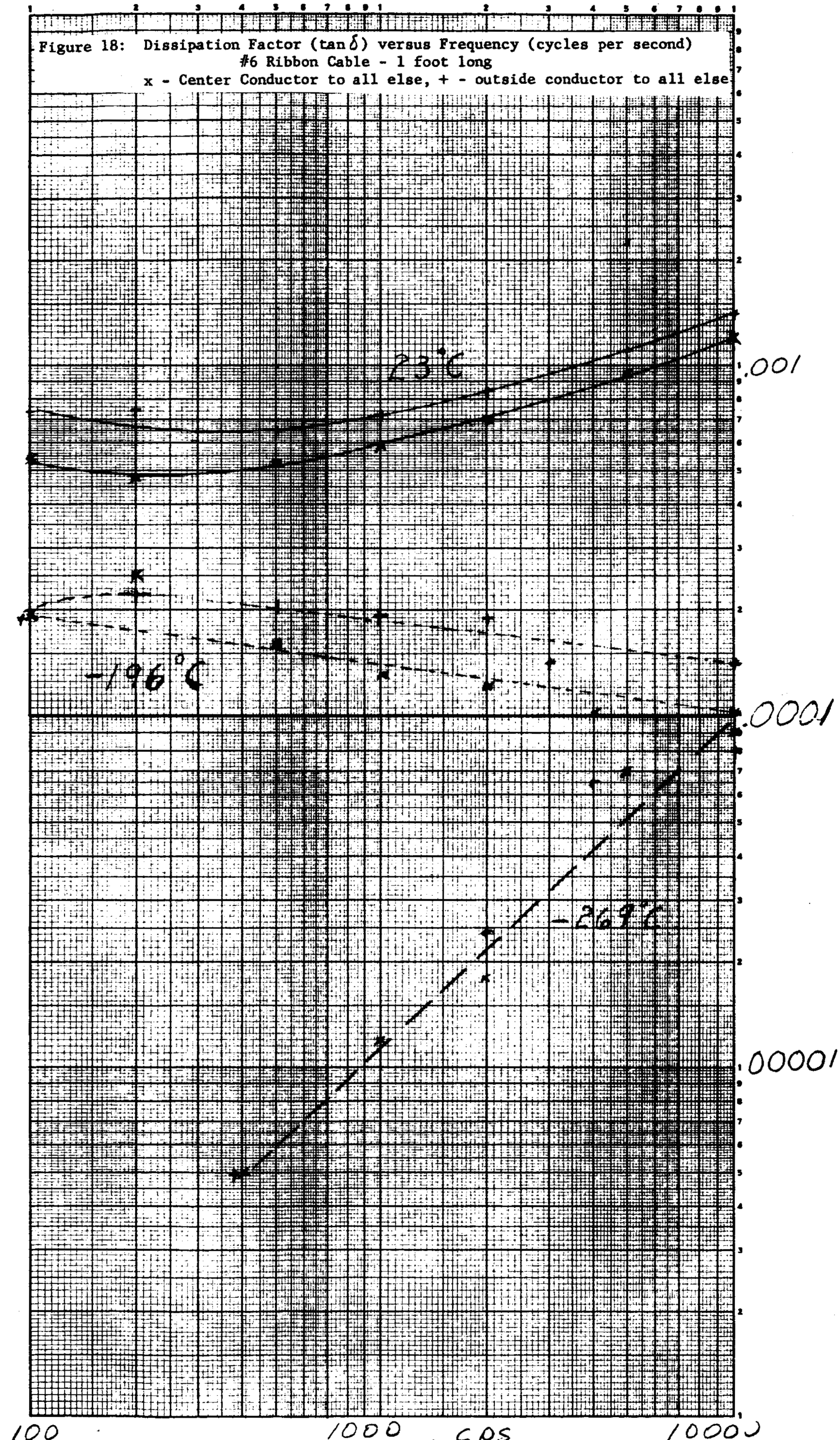


Figure 18: Dissipation Factor (tan δ) versus Frequency (cycles per second)
#6 Ribbon Cable - 1 foot long
x - Center Conductor to all else, + - outside conductor to all else
23°C
-196°C
-269°C
.001
.0001
.00001
100
1000
cps.
10,000

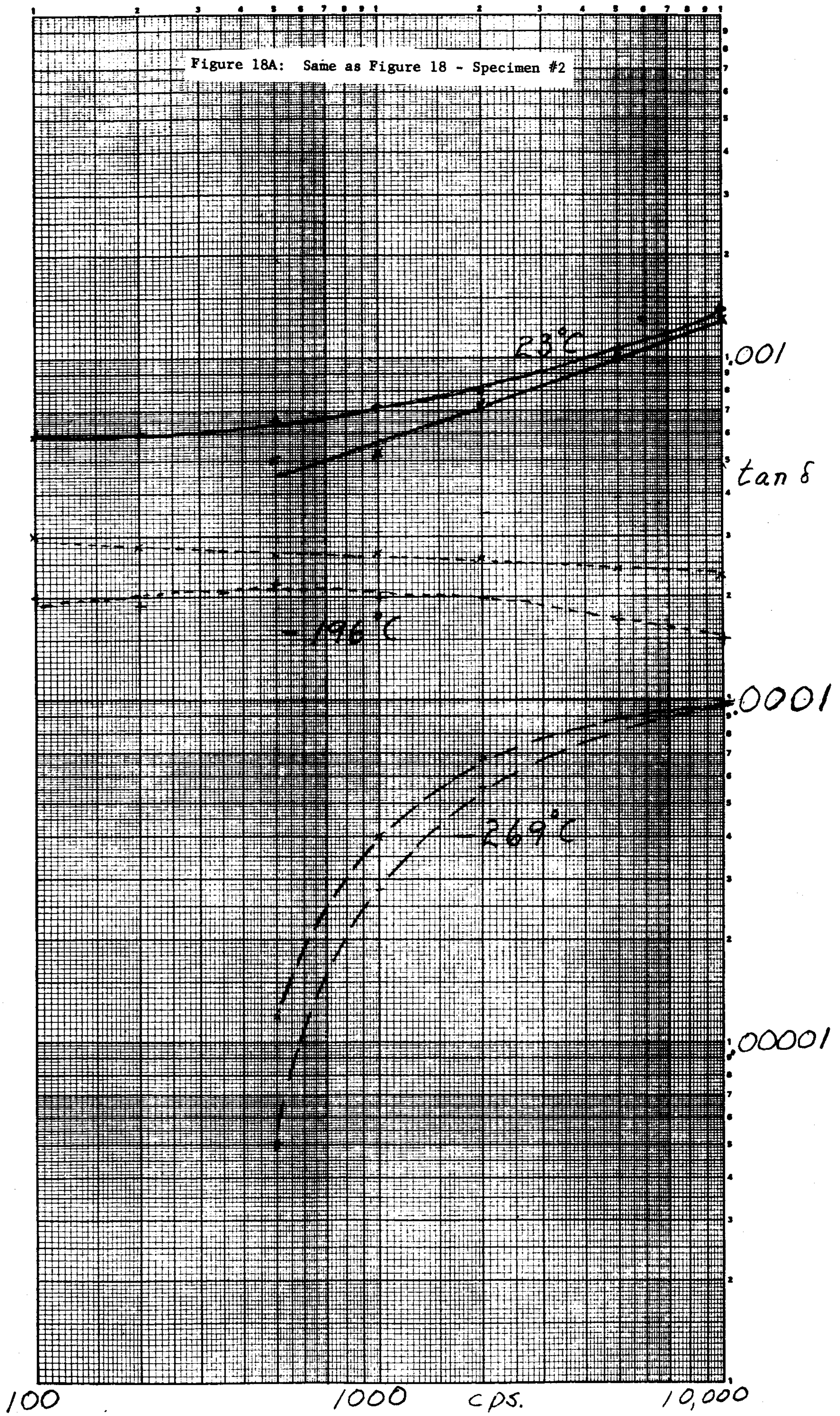


Figure 18A: Same as Figure 18 - Specimen #2
23°C
-196°C
-269°C
.001
tan δ
.0001
.00001
100
1000
cps.
10,000

TABLE XV

Calculated Series Resistance - ohms

Long Specimens - Cable #6

	Cable #6-1		Cable #6-2	
Length	35 feet	per ft.	49 feet	per ft.
D.C. resistance of the shield $-23^{o}C$	4.5^{5}	0.13	6.4	0.13
Calculated series				
A.C. resist. $-23^{o}C$	2.2	.063	2.9	.059
A.C. resist. $-196^{o}C$	1.5	.043	2.15	.044
A.C. resist. $-269^{o}C$	1.5	.043	2.15	.044

TABLE XVI

Capacitance - Ribbon Cable #6

Connector	Specimen No.	Capacitance at 1000 cps picofarads per foot 23C	-196C	-269C	% Δ Capacitance 100 to 10,000 cps 23C	-196C	-269C
All conductors to shield	1	1465	1485	1430	0.136	0.135	0.09(?)
	2	1480	1495	1425	0.125	0.136	0.14(?)
Center conductor to all else	1	118.5	121.0	115	0.246	0.112	.016(?)
	2	119.0	121.0	113	0.278	0.108	.037(?)
Outside conductor to all else	1	123.0	124.0	121	0.163	0.152	.031(?)
	2	120.0	121.0	116	0.124	0.088	.07(?)

(?) - Error due to inductance may be involved.